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RTD-TDR-63-1027

APPLIED RESEARCH AND DEVELOPMENT WORK ON FAMILIES OF BRAZED AND WELDED FITTINGS FOR ROCKET PROPULSION FLUID SYSTEMS

PHASE I. MATERIAL SELECTION, PROCESS DEVELOPMENT, AND PRELIMINARY DESIGN

TECHNICAL DOCUMENTARY REPORT NO. RTD-TDR-63-1027
November 1962

Rocket Propulsion Laboratory
Research and Technology Division
Air Force Systems Command
Edwards Air Force Base, California

Project No. 6753, Task No. 675304

(Prepared under Contract No. AF 04(611)-8177 by the
Los Angeles Division, North American Aviation, Inc.,
Los Angeles 9, California
M. H. Weisman, G. Martin, W. D. Padian,
S. Salmassy, T. Fan, G. Sine and J. West, authors.)

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NOTICES

FOREWORD

This Technical Documentary Report covers the work performed during Phase I of U.S. Air Force Contract No. AF 04(611)-8177. This Phase included the selection of materials for tubing and tube fittings for use in rocket propulsion fluid systems, the development of braze and weld parameters for joining these materials, the preliminary design of light-weight brazed and welded fittings, and the design and installation of facilities for qualification testing of brazed and welded fittings during the Phase II part of this program.

This contract is sponsored by the Research and Technology Division, Air Force Systems Command, U.S. Air Force, Edwards Air Force Base, California. It is established under Air Force Program Structure No. 750G, AFSC Project No. 6753, AFSC Task No. 675304, with 1/lt Philip Oleksyk of the Rocket Propulsion Laboratory, Liquid Systems Division, Propulsion Sub-systems Branch, as the USAF Project Engineer.

This program is being conducted in the Research Laboratory of the Los Angeles Division, North American Aviation, Inc., International Airport, Los Angeles 9, California. Mr. C. A. Fairbairn, Group Leader of the Metallic Materials Laboratory, is the Program Manager, and Mr. M. H. Weisman, Metallic Materials Laboratory, is the Project Engineer for the Contractor. Participating in the program work and in the preparation of this report, in the areas noted, were the following persons: Messrs. Dr. George Martin (Materials), W. D. Padian (Welding), S. Salmassy (Brazing), T. Fan (Structural Analysis), G. Sine and J. West (Qualification Test Program).

ABSTRACT

Recommendations are presented for lightweight brazed and welded fittings for use with rocket propulsion fluid systems. These recommendations are based on a literature survey on the compatibility of candidate materials with rocket propellants, and on the consideration of the effects of the fitting joining processes on the materials. Other parameters that could significantly affect the fitting classification and subsequent design, such as material cost and availability, and braze alloy shear strength, have been investigated. Joining procedures and preliminary designs have been developed for induction brazed and TIG welded fittings for tubing of AISI 347 stainless steel, AM 350 precipitation hardening stainless steel, and Rene' 41 alloy. Studies have also been conducted on the feasibility of brazed and welded fittings for use with aluminum tubing. Procedures have been prepared and the required facilities are being installed for qualification testing of the fittings and joining processes during the Phase II part of this program. The fittings will be tested to rigid requirements under the Qualification Tests and other future efforts of this program and the results will be documented.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

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1. INTRODUCTION

The systems and components of rocket propulsion vehicles must function under severe environmental and operational conditions. Rocket propulsion fluid systems, in particular, are subjected to extremes of temperature, pressure, vibration, and the effects of radiation encountered in space. The use of new and exotic propellants and other fluids has produced new problems of chemical activity and material compatibility.

The conventional aircraft-type fitting designs currently being used for tubing connections in rocket propulsion fluid systems have proven inadequate because of problems of corrosion, leakage, and fatigue failure. New advanced tube joining concepts are required which will provide zero leakage and light weight with high operational reliability.

Techniques for making in-place tubing connections by brazing and by welding have been developed by the Los Angeles Division of North American Aviation, Inc., for use on the X-15 and XB-70 air vehicles. These techniques are considered to be feasible for further development for joining tubing for advanced rocket propulsion fluid systems.

The purpose of this program is to develop, design, fabricate, and qualify families of lightweight brazed and welded fittings for service with rocket propulsion fluid systems. This program is being conducted in three phases: Phase I, Material Selection, Process Development, and Preliminary Design; Phase II, Detail Design, Fabrication, and Qualification Testing of the Fittings; and Phase III, Final Design of Fittings and Joining Tooling, Preparation of Specifications, and Reporting.

Phase I consisted of a literature survey of the compatibility of typical storable and cryogenic propellants and pressurizing gases with the candidate tubing and fitting materials and with the brazing alloys under consideration. Fitting materials and brazing alloys were selected. Brazing and welding process parameters for these materials were investigated and suitable joining procedures were developed. A stress analysis of the proposed fitting designs was prepared. A detailed plan for the qualification testing of the fittings during Phase II was prepared and submitted to the USAF Project Officer for approval. The facilities required for the qualification tests were designed and fabrication and installation of these facilities was initiated.

Phase II consists of detail design of the prototype joining tooling required to fabricate the fittings for qualification test, the detail design of these fittings, and the performance of the qualification tests.

Phase III of the program consists of the final design of the fittings and production-type joining tooling, and the preparation of drawings, specifications, and test requirements for the fittings and the joining tooling in such a manner that military specifications and standards may be published. The fitting hardware selected by the Procuring Agency will be fabricated and delivered. A Final Report covering the entire program, and containing a detailed stress analysis of the fittings, will be prepared and submitted.

The Phase I part of the program has been completed and the work conducted and results obtained during this Phase are presented in this report.

2. MATERIAL SELECTION

2.0 GENERAL CONSIDERATIONS

Rocket propulsion fluid system tubing and fittings are required to meet service temperatures and pressure schedules such as those shown in Table I, and to be compatible with the system fluids and operational environment. An added requirement which must be fully considered under this program is the effects which the braze or weld joining processes may have on the tubing and fitting materials and their resultant suitability for use in particular systems. The primary factors which must be considered in material selection are:

(1) Chemical compatibility with the system fluids listed in Table II.

(2) A high strength/weight ratio at the maximum service temperature for the system as shown in Table I.

(3) Ability to be satisfactorily joined by brazing and/or welding processes being developed under this program.

(4) Commercial availability of the material in suitable forms and shapes.

Additional factors which are also important are:

(5) Machinability.

(6) Cost.

(7) Accelerated fatigue damage or embrittlement due to service conditions, such as temperature shock, vibration, etc.

(8) Sensitivity to radiation or space environment.

The welding and brazing properties of the materials will be discussed in the appropriate sections later in this report. The other factors listed above will be discussed in the following paragraphs.

The mechanical, physical, and chemical properties important in selecting materials for rocket fluid systems, in many cases, vary as a function of the operating temperature range of the system. The lower temperature range of the service environment for the systems considered under this program is -423 F, the temperature of liquid hydrogen, for the propellant system, and -320 F, the temperature of liquid nitrogen, for the pneumatic systems. Testing under this program will be conducted at temperatures only as low as -320 F for both types of systems. The upper temperature limit for the propellant system and one type pneumatic system are 200 F, for the second type pneumatic system 600 F, and 1500 F for the third type pneumatic system. The fitting classification service environments and the rocket system fluids to be considered under this program are presented in Tables I and II, respectively.

TABLE I

FITTING CLASSIFICATION

SERVICE	SYSTEM OPERATING PRESSURE RANGE	SYSTEM OPERATING TEMPERATURE RANGE	SYSTEM TUBING DIMENSIONAL RANGE
Propellant	0 to 2500 psig	-423 F to 200 F	1 to 2 inches in 1/4 inch increments 2 to 3 inches in 1/2 inch increments 3 to 5 inches in 1 inch increments 6 to 16 inches in 2 inch increments
Pneumatic	0 to 3000 psig	-320 F to 200 F	1/8 to 1/4 inch in 1/16 inch increments
	0 to 1000 psig	-320 F to 200 F	5/16 to 1 inch in 1/16 inch increments
	0 to 10,000 psig	-320 F to 600 F	1/8 to 1 inch in 1/16 inch increments
	0 to 4000 psig	-320 F to 1500 F	

TABLE II

ROCKET SYSTEM FLUIDS TO BE CONSIDERED FOR USE WITH LIGHTWEIGHT BRAZED AND WELDED FITTINGS

Fitting Service Classification	Fluid Type Classification	Description of Rocket System Fluid
Propellant	Storable Propellants	(a) UDMH-Hydrazine Blends (0 to 100 percent N_2H_4) (b) Hydrogen Peroxide (c) Nitrogen Tetroxide (d) Chlorine Trifluoride (e) Pentaborane (f) Red Fuming Nitric Acid (g) White Fuming Nitric Acid (h) RP-1 (i) MMH (j) N_2F_4
	Cryogenic Propellants	(k) Liquid Oxygen (l) Liquid Hydrogen (m) Liquid Fluorine (n) OF_2 (o) ClO_3F
Pneumatic	Ambient Temperature Gases	(p) Gaseous Oxygen (q) Gaseous Hydrogen (r) Gaseous Nitrogen (s) Gaseous Helium
	Elevated Temperature Gases	(t) High Temperature Hydrogen Gas (u) High Temperature Helium Gas (v) High Temperature Combustion Products Associated with solid and Liquid Propellants Reactions (Flow Rates of the order of two (2) pounds per second)

2.1 CHEMICAL COMPATIBILITY

The primary requirement of a material to be used for tubing or fittings in rocket propulsion fluid systems is that it be chemically compatible with the fluids to be contained. This compatibility must be mutual; that is, the fluid must not attack the system material and cause a reduction in the material strength, nor must the system material itself cause any change in the composition of the fluid, either by direct or catalytic action. Chemical attack by the fluid on the system material generally implies a surface corrosion action which reduces the effective thickness of the tubing or fitting and thus reduces its strength. Other factors to be considered are stress corrosion attack and the formation of loose corrosion products or of sludge which may block passages or interfere with the operation of valves.

The braze and weld processes for joining tubing and fittings which are being developed under this program introduce factors which can considerably complicate the compatibility problem. The usual dissimilarity which exists between a brazing alloy and the materials being joined cause brazed joints to have an inherent chemical inhomogeneity, the effect of which must be evaluated. The problem of material dissimilarity in welded joints can be minimized by proper selection of the tubing, fitting, and weld filler materials. Some chemical compatibility difficulties may still arise in welded joints, however, due to such causes as differences in the metallurgical structure or heat treat condition of the several joint materials.

One of the principal problems in assessing the compatibility of the system materials with the fluids contained is the general scarcity of comprehensive and reliable data. Complete information on the materials and test conditions are available in only a few cases. Many compatibility data which appear in the literature do not specify the state of heat treatment of the test material. Few, if any, tests seem to have been conducted on stressed materials exposed in the fluids listed in Table II for consideration under this program.

A review of the technical literature was conducted to gather information on the chemical compatibility and other properties of candidate tubing and fitting materials with the rocket propulsion system fluids considered in this program. The most valuable literature sources are listed in the REFERENCES section at the end of this report and are also referred to in specific areas below. Additional data were obtained from tests which had previously been conducted by the several divisions of North American Aviation, Inc. This information on the chemical compatibility of a number of tubing and fitting materials with the propulsion system fluids and pressurizing gases considered in this program is presented in summary form in Table III. In addition to this information, the following comments are relevant to the various groups of fluids and gases.

TABLE III. RECOMMENDATIONS CONCERN
CANDIDATE MATERIALS WIT

MATERIAL TYPE	N_2H_4	UDMH-N_2H_4 BLEND(3)	UDMH and MMH	N_2O_4	WFNA and RFNA	H_2O_2	ClF_3 (4)	OF_2 (4)	ClO_3F (4)	F_2 (4)	N_2
STAINLESS STEELS											
304L	A(1)	B(1)			B(2)					B(10)	
316	C(1)	C(1)									
321	B(1)	B(1)	B(1)	A(2)	A(2)	B(2)	B	B	B		
347										B(6)(10)	
A-286	C(1)	C(1)			B(2)						
17-7PH	B(1)	B(1)					C			D	
350	C(1)(5)	C(1)(5)		B(2)							
355			C(1)(5)		C(2)(5)	C(2)(6)	C(5)	C(5)	C(5)		
HEAT RESISTING ALLOYS											
Monel	D	D	D	D	D			B(11)	B(11)		
K-Monel								A			
Inconel	A(1)							B(11)			
Inconel X	B(1)					D	A		A	A(10)	
Inconel 718	B(1)	B(1)	A	A(1)	B(2)			A			
Rene' 41	A(1)										
Hastelloy C	D	D	C	B(1)				A(7)	B(7)		
ALUMINUM ALLOYS											
EC						A(2)(9)					
1100	A(1)										
3003	B(1)	B(1)	B	A(1)(9)	A(2)(9)	B(2)(9)	B	B	B(1)	A(10)	
6061	A(1)										
2024	D	D	C	D	D	D		B(11)			
MISCELLANEOUS METALS											
Tantalum	A(1)			A	A(2)	A(2)	A	A(11)	A(11)	A(10)	
Titanium		A	A	B(5)			D	D	D	D	
Nickel	C(1)			D			A(3)	A(11)	A(11)	A(10)	
Copper	D	D	D				B(2)				
Magnesium					D	D		B(2)	B(2)	B(2)(10)	
Gold	-	A	A	B			B	B	B	B(8)(10)	
Silver	D	B	B	D			D	D	D	D	

TABLE III. RECOMMENDATIONS CONCERNING CHEMICAL COMPATIBILITY OF CANDIDATE MATERIALS WITH ROCKET PROPELLANT FLUIDS.

H_2O_2	ClF_3 (4)[3]	OF_2 (4)	ClO_3F (4)	F_2 (4)	N_2F_4	RP-1
(2)	B	B	B	B(10)	A	A
				B(6)(10)		
	C			D	D	
(2)(6)	C(5)	C(5)	C(5)			B(10)
		B(11)	B(11)		A	C
		A				
		B(11)				
D	A	A	A	A(10)	---	A
		A(7)	B(7)			
(2)(9)						
(2)(9)	B	B	B(1)	A(10)	---	A
D		B(11)				C
A(2)	A	A(11)	A(11)	A(10)	A	A
	D	D	D	D	D	
	A(3)	A(11)	A(11)	A(10)		
					A	D
D	B(2)	B(2)	B(2)	B(2)(10)	-	A
	B	B	B	B(8)(10)		
	D	D	D	D	D	

EXPLANATION OF SYMBOLS AND NOTATIONS:

A	Material suitable for unlimited service involving long-term storage of propellant.
B	Material suitable for storage of propellant under limited conditions, and for short-term contact prior to storage of propellant.
C	Material suitable only for short-term contact prior to use of propellant.
D	Material not suitable for use with propellant.

(1) Service limited to 160 F maximum and with dry propellant.
(2) Materials must be suitably passivated prior to use with propellant.
(3) 50/50 blend by weight of UDMH and N_2H_4.
(4) Use of all metals is contingent on suitable stabilization. Extended service of stainless steels in these propellants may result in heavy deposits of fluorides. Systems utilizing stainless steel should be flushed after each use at high temperature to remove fluoride deposits.
(5) May be susceptible to chemical attack by propellant.
(6) May be susceptible to stress corrosion by propellant.
(7) Service limited to 160 F maximum.
(8) Attacked by dry fluorine at temperatures above 590 F.
(9) Suitable only for short-time use in systems where metals other than aluminum alloys are also in contact with propellant because of resulting preferential chemical attack on aluminum alloys by propellant.
(10) Suitable for use with dry propellant only.
(11) Service limited to 212 F maximum.

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Hydrazine and Derivatives

Hydrazine (N_2H_4), hydrazine derivatives such as UDMH (unsymmetrical dimethylhydrazine) and MMH (monomethyl hydrazine), and mixtures of these fluids exhibit only minor differences in their compatibility with candidate tubing and fitting materials. In the dry state and at temperatures below 160 F these propellants are compatible with a variety of materials; but when moist, hydrazine tends to attack the stainless steels, References (4), (5) and (6).

Inconel is the tubing or fitting material which is most compatible for use with hydrazine and its derivatives. Tantalum, Rene'41, aluminum and some aluminum alloys are also satisfactory for use with hydrazine and hydrazine derivatives.

Welding has been found to be a satisfactory method of joining the above materials for service with hydrazine and hydrazine derivatives. The only information available on the compatibility of brazed joints for use with hydrazine and its derivatives is for silver brazed joints with brazing alloys such as Easyflow 45. The data indicate that silver brazed joints are compatible for use with hydrazine and its derivatives.

Fuming Nitric Acids

Only a few materials are satisfactory for use as tubing and fittings with the fuming nitric acids. As shown in Table III, these materials include tantalum and several of the stainless steels. Aluminum and several of the aluminum alloys are suitable for use with the fuming nitric acids if the acid will not also contact other metallic materials. Systems in which other metals as well as aluminum alloys will be in contact with fuming nitric acids are suitable only for short time use. In such systems the aluminum and aluminum alloy components are subject to preferential galvanic attack by the propellant. See References (4) and (6).

Titanium and titanium alloys should never be used for systems to contain fuming nitric acids. Under certain conditions the fuming nitric acids react with titanium and titanium containing metals to form compounds which are extremely shock sensitive. Violent reactions may then occur, particularly when such compounds are in contact with the fuming nitric acids, References (4) and (7).

Welding is indicated to be the preferred method of joining materials for service in fuming nitric acid systems. The compatibility and corrosion resistance of brazed joints for fuming nitric acid service could not be established on the basis of the data available, although noble metal brazing alloys such as gold-palladium appear to be promising.

The use of stainless steels for components of fuming nitric acid systems which are assembled by welding or which may be exposed at times to temperatures above 700-800 F involves certain problems. Even with the stainless steel alloys which are listed in Table III as compatible with fuming nitric acids, care must be taken to eliminate the effects of any carbide precipitation reactions which may result or to avoid such reactions entirely. Such adverse reactions in stainless steels are generally avoided by use of the stabilized AISI 321 and AISI 347 alloy grades. Weldments of these alloys are normally satisfactory for use in the as-welded condition. However, unless properly heat treated by solution annealing after welding, the weld areas of even these stabilized stainless steels are susceptible to stress corrosion by the fuming nitric acids. Adverse carbide precipitation effects may be minimized by the use of extra-low carbon stainless steels, which should therefore be specified for service with fuming nitric acids for parts which are to be welded.

Nitrogen Tetroxide

The compatibility of tubing and fitting materials with nitrogen tetroxide (N_2O_4) is generally considered to be similar to the compatibility of the materials with the fuming nitric acids. The specific recommendations shown in Table III were prepared on the basis of the survey of the technical literature. In the interpretation of these recommendations it should be noted that nitrogen tetroxide, in the presence of free water, will ionize in such a manner that it may behave the same as a fuming nitric acid. Because of this possibility the literature recommends that when certain materials, such as titanium and its alloys, are considered for nitrogen tetroxide service, that tests be made of the proposed application in the configuration that the materials will be used and under the conditions to which they will be subjected during the anticipated service lifetime. See References (4), (6), (8), (9), (10) and (11).

Fluorine and Fluorine Compounds

Fluorine and fluorine compounds such as oxygen difluoride (OF_2), perchloryl fluoride (ClO_3F), chlorine trifluoride (ClF_3), and nitrogen fluoride (N_2F_4) are considered together. Most metals and alloys with a high oxidation resistance are suitable for use with these propellant fluids. Monel and the stainless steels, in general, are the preferred materials. However, the AISI 347 stainless steel grade has been reported to be susceptible to stress corrosion by liquid fluorine, References (4) and (12). These materials are usually subjected to a passivating treatment prior to use with these fluids. See References (4), (6) and (12). This treatment produces a passive fluoride film on the metal surfaces which then protects the surfaces from further attack by the fluoride propellant fluid.

Extended service of stainless steels in these propellants may result in heavy deposits of fluorides on the metal surfaces, Reference (13). No data are available on the effects of fast moving streams of propellants which might disturb or erode the passivated protective fluoride films and thus increase the corrosion rate.

Striking, repeated bending, flexing, or excessive vibration of fluoride propellant piping or tankage should be avoided. Such mechanical actions can result in flaking, cracking, or breaking of the protective fluoride film on the internal surfaces of the system. With certain of these propellants, such as chlorine trifluoride, this can result in a rupture of the metal and a possibly violent reaction between the metal and the propellant. Flaking of the protective film can produce particles which may interfere with valve operation or block small tubing lines, References (4) and(14).

Welded joints are recommended to connect piping and tankage for handling these propellant fluids.

No data are available on the compatibility of nitrogen fluoride (N_2F_4) with metals. Tentative recommendations for N_2F_4 materials compatibility which are given in Table III were obtained from Reference (13).

<u>Boranes</u>

These propellants do not present a material compatibility problem. All commercial metals and alloys are suitable for use with the borane compounds. It is very important that systems containing the borane compounds be sound and leaktight because of the extreme toxicity of the borane compounds.

<u>Hydrocarbon Fuels</u>

No special corrosion problems are experienced with RP-1 or other hydrocarbon propellant fluids, although excessive moisture in the fluid may cause corrosion or rusting in materials subject to atmospheric corrosion. Such corrosion problems may be aggravated by galvanic couples produced by the presence of brasing alloys or combinations of dissimilar metals in a system.

<u>Hydrogen Peroxide</u>

The main problem connected with the selection of materials for fabrication of hydrogen peroxide (H_2O_2) fluid systems is not so much the attack of the fluid on the materials but, rather, the effect of many materials on the decomposition of the hydrogen peroxide, Reference (4).

High purity aluminum, the 5000 series of aluminum alloys, and tantalum appear to be the only materials which are fully satisfactory for extended storage of hydrogen peroxide. Under short-term contact conditions it becomes possible to use a wider variety of alloys including, principally, the AISI 300 series stainless steels without adverse service compatibility effects.

Experience with the hydrogen peroxide system on the X-15 rocket powered aircraft has shown that problems arise when aluminum tubing and fittings are used in connection with other materials, such as stainless steels. The electro-chemical problems which resulted were such that aluminum and aluminum alloys have been eliminated from the tubing and tankage systems for hydrogen peroxide on the X-15. Aluminum tubing, therefore, should be considered only for an all-aluminum structure, unless the aluminum materials can be electrically insulated from the other materials in the system.

Surface finish is a factor in determining compatibility of materials with hydrogen peroxide. The smoother the surface, the less is the chance of there being undesirable effects, such as liquid-phase decomposition of the hydrogen peroxide. Therefore, it is necessary to ensure that the joints present as little discontinuity as possible in hydrogen peroxide systems. See Reference (4).

Materials such as Hastelloy B and C, and 19-9DL stainless and heat resisting steel, may be used only for short-time contact with hydrogen peroxide. These materials may cause contamination of hydrogen peroxide solutions sufficient as to make them unfit for storage, Reference (4).

The following materials are considered unsuitable for any use with hydrogen peroxide solutions. In general, they may cause rapid decomposition of the hydrogen peroxide, are rapidly attacked, or form explosive mixtures with hydrogen peroxide. Such materials include copper and copper alloys, lead, the AISI 400 series stainless steels, magnesium, zinc, and gold and silver alloys, Reference (4).

Liquid Oxygen and Liquid Hydrogen

Materials selected for tubing systems and fittings for use with liquid oxygen or liquid hydrogen must have adequate strength and toughness at cryogenic temperatures. The strength of materials increases as the temperature decreases; but, generally, materials lose toughness and become brittle or notch sensitive at cryogenic temperatures. Toughness of the material at low temperatures, therefore, becomes the controlling factor. The AISI 300 series austenitic stainless steels, most aluminum alloys, nickel alloys, and superalloys are satisfactory.

Materials for use with liquid oxygen must not undergo self-propagating reactions with the liquid oxygen. Such materials must be tested for shock sensitivity under service conditions, particularly as regards reactions on freshly cut surfaces. Titanium and titanium alloys ignite with liquid oxygen. The reaction will propagate and completely consume the titanium, Reference (11). Therefore, titanium and titanium alloys cannot be used for liquid oxygen systems.

Hot Exhaust Gases

The principal material requirement for hot exhaust gas system use is good high temperature strength. Any chemical reactions are likely to be greatly accelerated at high temperature. Therefore, traces of propellants which may be present in the hot gas stream are likely to be more corrosive than under normal storage conditions. The interaction between combustion products and metals has been studied recently, and the the first results are described in Reference (15). It is generally concluded from these initial studies that the interaction can be predicted from thermodynamic data, except where metallurgical diffusion reactions, such as the formation of carbides, occur.

Recommendations for Compatibility and Corrosion Testing

The lack of reliable information on the chemical compatibility of the candidate materials for tubing and fittings with the fluids used in rocket propulsion systems makes it highly desirable that these materials be tested under service environment type conditions prior to general use. At least one representative member of each of the various rocket propulsion system fluid types should be selected as the corrosive environment medium. The fluid types which are suggested for use in the tests include a hydrazine compound, hydrogen peroxide, a fluoride compound, and nitrogen tetroxide.

In order to obtain results which can be expected to represent those which may occur in service, the tests should include a stressing factor to determine the susceptibility of the material to stress corrosion, a joining factor, and a space service factor. The joining factor will indicate the effects of electro-chemical action or of changes in the metallurgical structure of the tubing and fitting materials due to the presence of a brazing alloy and any heat treatment changes caused by the braze or weld cycles. Space service factors are those which are likely to affect materials with a high vapor pressure, such as cadmium or silver, both commonly used in brazing alloys. These same factors can affect many other materials which may develop appreciable vapor pressures at high temperatures. Radiation effects such as may occur in materials subject to space environments are complex and depend greatly on the type of radiation encountered. Vehicles in space will be exposed to primary cosmic radiation, which consists primarily of protons but also includes particles of higher mass. No detrimental effects are anticipated from cosmic rays in the metallic materials being considered under this program. In the Van Allen radiation belts, vehicles will be exposed to mainly electrons of energy greater than 13 Mev and to protons whose energy ranges to 700 Mev, Reference (16).

The radiation flux in the Van Allen belts can range from 10 roentgens per hour to as high as 1000 roentgens per hour, depending on solar conditions, Reference (16). The radiation exposure of a satellite orbiting under these conditions in the Van Allen belts for a period of two years would range from approximately 10^7 to 10^9 ergs per gram of carbon equivalent. By way of comparison, metals used in nuclear reactors are exposed to fluxes 10^5 to 10^6 times as great.

Exposure to cosmic ray or Van Allen belt radiation conditions for as long as several years is not considered damaging to metals. Damaging effects are produced in metals by exposure to fast or thermal neutron radiation. Such radiation is generated in nuclear reactors, but is not considered to be a factor in the radiation existing in space or in the Van Allen belts. Therefore, no general radiation tests are suggested here. Such tests, if desired, should be planned to fit the conditions established when details of specific types of missions are specified.

Studies of corrosion and of vacuum or space environment effects can be carried out using a number of different types of standardized specimens. Results which are most representative of service will be obtained if the tests are carried out on stressed specimens which incorporate welded and/or brazed joints. This type of specimen will permit the simultaneous evaluation of both the stress and the electro-chemical factors. A number of corrosion and stress corrosion tests of fairly standardized types in general use throughout industry are presented in Reference (17).

A novel specimen for stress corrosion testing of sheet materials is under development by the Contractor. This specimen consists of one or two strips which are restrained in a bent shape by being joined at the ends to a shorter third strip which acts as a tension member. The tension strip may contain a brazed joint, and the ends of the bent strips can be joined to the tension strip ends by welding, so that either or both brazing and welding effects may be observed. By a choice of suitable dimensions, the stresses in the assembled specimen can be made such that the maximum bending stress in the bent strips and the tensile stress in the shorter tension strip are equal to each other and are some particular desired value, such as a certain percentage of the yield strength of the material. Details of this specimen and of the calculations required to select the specimen size and test stress level will be completed during the Phase II part of this program.

2.2 STRENGTH CONSIDERATIONS

General Strength Parameters

Following the determination of satisfactory compatibility with the rocket propulsion system fluids, the selected candidate materials are then further evaluated against the following strength requirements. The necessity to minimize the weight of rocket propulsion vehicles makes it extremely important to consider the strength-to-weight ratio of constructional materials. The term "strength," as used here, implies the effective strength of the material under service conditions. As a first approximation, the 0.2 percent offset yield strength as determined by a short-time test at the maximum service temperature can be taken as a measure of the usable strength of the material, although the following factors must be taken into account.

(1) Instability of the metallurgical structure. This can lead to either progressive softening and loss of strength during high temperature service or to hardening and possible embrittlement after a period of elevated temperature service.

(2) Embrittlement effects resulting from stress corrosion or similar phenomena.

(3) Fatigue failure in installations subject to repeated stress cycling or vibration.

(4) Fracture toughness; that is, the ability of a material to contain cracks or defects without suffering a significant loss of strength. This factor is considered less important than the other factors listed above so far as the selection of materials for tubing and fittings is concerned. This is because even small stable (non-progressing) cracks and similar defects which penetrate through the wall of a tube would disqualify the tube because of leakage or loss of system pressure.

(5) Creep strength for applications involving service at elevated temperature for significant periods of time.

The modulus of elasticity of materials is important because both structural stiffness and the strain resulting from bending or from internal pressure stress are a function of the modulus of elasticity. It is desirable to use a material with as high a modulus as possible in order to maximize the stiffness of the component and minimize the resulting strain.

Strength Properties of Tube and Fitting Materials

The chemical compositions of candidate materials for tubing and fittings are presented in Tables IV, V, and VI. Tensile ultimate and yield strengths, tensile modulus of elasticity, and coefficient of linear thermal expansion values versus temperature are presented in Table VII for the most applicable candidate materials. Note must be taken of the heat treatment or condition of the materials as listed in Table VII. Fully heat treated materials, of course, have a high strength. However, in the case of welded and/or brazed fittings it is usually not possible to heat treat the connection after joining when in-place joining procedures are used. It is necessary, therefore, to consider the minimum properties as exhibited by the material in the annealed or "as welded" condition when evaluating the strength of materials to be used for systems on which in-place joining procedures are to be used. Unfortunately, reliable data on annealed properties are not available for many materials as this information is not usually considered to be of structural significance. In the case of welded and brazed fittings, the annealed and "as welded" strength properties of materials are required to determine the reduction in strength across the joint which may have to be accepted. The information presented in Table VII are taken principally from Reference (18), the NAA Material Properties Data Manual, and also from supplier brochures, such as Reference (19).

In addition to the short-time elevated temperature strength, there are other effects of service temperatures on material properties which must be considered. Service at high temperatures may produce creep effects. Service under cryogenic conditions may cause brittleness and low notch toughness, or notch sensitivity. The problem of low temperature brittleness can be reduced by the choice of metals and alloys having a predominantly face-centered cubic lattice structure. Such materials are the austenitic stainless steels, aluminum and its alloys, and some superalloys.

TABLE IV. COMPOSITION OF ALUMINUM ALLOYS

TYPE	COMPOSITION (Percent)								
	Manganese	Copper	Zinc	Iron	Silicon	Magnesium	Chromium	Titanium	Aluminum
EC	0.01 max	0.10 max	0.10 max	0.50 max	0.15 max	0.01 max	0.01 max	(a)	99.45 min
1100	0.05 max	0.20 max	0.10 max	1.00 max		—	—	—	99.00 min
2014	0.40 to 1.2	3.9 to 5.0	0.25 max	1.00 max	0.5 to 1.2	0.2 to 0.8	0.10 mix	0.15 max	Remainder
2024	0.30 to 0.9	3.8 to 4.9	0.10 max	0.50 max	0.50 max	1.2 to 1.8	0.10 max	—	Remainder
5052	0.10 max	0.10 max	0.10 max	0.45 max		2.2 to 2.8	0.15 to 0.35	—	Remainder
6061	0.15 max	0.15 to 0.40	0.25 max	0.70 max	0.4 to 0.8	0.8 to 1.2	0.15 to 0.35	0.15 max	Remainder
7075	0.30 max	1.2 to 2.0	5.1 to 6.1	0.70 max	0.50 max	2.1 to 2.9	0.18 to 0.40	0.20 max	Remainder
356	0.10 max	0.20 max	0.20 max	0.50 max	6.5 to 7.5	0.2 to 0.4	—	0.20 max	Remainder
Tens 50	0.10 max	0.20 max	0.20 max	0.50 max	7.8 to 8.6	0.4 to 0.55	(b)	0.1 to 0.2	Remainder
4043	0.05 max	0.30 max	0.10 max	0.80 max	4.5 to 6.0	0.05 max	—	0.20 max	Remainder

Notes: (a) Contains Boron 0.01 to 0.06 percent which must exceed the Titanium plus Vanadium.

(b) Contains Beryllium 0.1 to 0.3 percent.

TABLE V. COMPOSITION OF STAINLESS STEELS

TYPE	COMPOSITION (Percent)							
	Carbon maximum	Manganese maximum	Silicon maximum	Chromium	Nickel	Molybdenum	Titanium	Other (a)
302	0.15	2.00	1.00	17.00 to 19.00	8.00 to 10.00	—	—	—
303	0.15	2.00	1.00	17.00 to 19.00	8.00 to 10.00	(b)	—	0.15 min S
304L	0.03	2.00	1.00	18.00 to 20.00	8.00 to 12.00	—	—	—
316	0.08	2.00	1.00	16.00 to 18.00	10.00 to 14.00	2.00 to 3.00	—	—
321	0.08	2.00	1.00	17.00 to 19.00	9.00 to 12.00	—	5 x C min	—
347	0.08	2.00	1.00	17.00 to 19.00	9.00 to 13.00	—	—	10 x C min Cb-Ta
A-286	0.08	1.00 to 2.00	0.4 to 1.0	13.50 to 16.00	24.00 to 27.00	1.00 to 1.50	1.90 to 2.35	0.35 max Al, 0.001 to 0.010 B, 0.10 to 0.50 V
350	0.08 to 0.12	0.50 to 1.25	0.50	16.00 to 17.00	4.00 to 5.00	2.50 to 3.25	—	0.07 to 0.13 N
355	0.10 to 0.15	0.50 to 1.25	0.50	15.00 to 16.00	4.00 to 5.00	2.50 to 3.25	—	0.07 to 0.13 N
17-4PH	0.07	1.00	1.00	15.50 to 17.50	3.00 to 5.00	—	—	3.00 to 5.00 Cu 0.15 to 0.45 Cb+Ta
17-7PH	0.09	1.00	1.00	16.00 to 18.00	6.50 to 7.75	—	—	0.75 to 1.50 Al
PH15-7Mo	0.09	1.00	1.00	14.00 to 16.00	6.50 to 7.75	2.00 to 3.00	—	0.75 to 1.50 Al

Notes: (a) Remainder is Iron.

(b) Molybdenum or Zirconium 0.60 maximum.

TABLE VI.. COMPOSITION OF HEAT-RESISTING ALLOYS

TYPE	NOMINAL COMPOSITION (Percent)																
	C	Mn	Si	Cr	Ni	Co	Mo	Ti	Fe	Al	Cu	Cb	Ta	W	B	Zr	V	S
Monel	0.1	1.1	0.35	—	67.0	—	—	—	1.3	—	30.0	—	—	—	—	—	—	0.01
K-Monel	0.15	0.7	0.50	—	66.0	—	—	—	0.9	2.75	29.0	—	—	—	—	—	—	0.005
Inconel	0.04	0.35	0.20	15.0	78.0	—	—	—	7.0	—	—	—	—	—	—	—	—	—
Inconel X	0.04	0.70	0.30	15.0	73.0	—	—	2.5	7.0	0.9	—	1.0	—	—	—	—	—	—
Hastelloy C	0.10	0.8	0.7	16.0	Rem.	—	17.0	—	5.5	—	—	—	—	4.0	—	—	—	—
Waspalloy	0.05	0.8	0.7	19.0	Rem.	13.5	4.3	2.5	1.0	1.3	—	—	—	—	0.005	0.06	—	—
Rene' 41	0.10	—	—	19.0	Rem.	11.0	10.0	3.0	3.0	1.5	—	—	—	—	0.005	—	—	—
Inconel 718	0.04	0.3	0.5	19.0	Rem.	0.5	3.0	0.8	18.0	0.6	0.3	Cb+Ta:5.0		—	—	—	—	—
Haynes 25	0.12	1.5	0.5	20.0	10.0	Rem.	—	—	1.5	—	—	—	—	15.0	—	—	—	—

TABLE VII. MATERIALS PROPERTIES RECOMMENDED FOR USE IN I

MATERIAL			DENSITY	PROPERTY (a)				
ALLOY	CONDITION	FORM	lb/cu.in.	SYMBOL	UNITS	-320F	-100F	ROOM
Type 347 Stainless Steel	Annealed	Sheet	0.286	F_{tu}	ksi	—	—	75.0
				F_{ty}	ksi	—	—	30.0
				E_t	psi x 10^6	—	—	29.0
				α	in./in./°F x 10^{-6}	—	—	8.9
AM 350 Stainless Steel (c)	Cold Reduced and Tempered Cond CRT	Tubing	0.282	F_{tu}	ksi	—	—	185.0
				F_{ty}	ksi	—	—	147.0
				E_t	psi x 10^6	—	—	28.7
				α	in./in./°F x 10^{-6}	—	—	—
	Sub-zero Cool and Tempered Cond SCT	Tubing	0.282	F_{tu}	ksi	—	—	220.0
				F_{ty}	ksi	—	—	192.0
				E_t	psi x 10^6	—	—	28.7
				α	in./in./°F x 10^{-6}	—	—	6.1
AM 355 Stainless Steel	Sub-zero Cool and Tempered Cond SCT	Bar	0.282	F_{tu}	ksi	—	—	200.0
				F_{ty}	ksi	—	—	165.0
				E_t	psi x 10^6	—	—	28.7
				α	in./in./°F x 10^{-6}	—	—	6.2
	As Welded or As Brazed (c)	Bar	0.282	F_{tu}	ksi	—	—	141.0
				F_{ty}	ksi	—	—	54.0
				E_t	psi x 10^6	—	—	—
				α	in./in./°F x 10^{-6}	—	—	—
Rene' 41 Heat Resisting Alloy	Heat Treated 1950F-½hr,WQ, 1400F-16hr,AC	Sheet and Bar	0.298	F_{tu}	ksi	—	—	170.0
				F_{ty}	ksi	—	—	130.0
				E_t	psi x 10^6	—	—	31.0
				α	in./in./°F x 10^{-6}	—	—	—
	As Welded or As Brazed	Sheet	0.298	F_{tu}	ksi	—	143.0	130.0
				F_{ty}	ksi	—	95.0	85.0
				E_t	psi x 10^6	—	—	—
				α	in./in./°F x 10^{-6}	—	—	—
Hastelloy C Heat Resisting Alloy (b)	Annealed	Sheet	0.323	F_{tu}	ksi	—	—	121.[illegible]
				F_{ty}	ksi	—	—	57.[illegible]
				E_t	psi x 10^6	—	—	29.[illegible]
				α	in./in./°F x 10^{-6}	—	—	6.[illegible]
6061 Aluminum Alloy	Heat Treated to -T6	Sheet	0.098	F_{tu}	ksi	56.0	46.0	42.[illegible]
				F_{ty}	ksi	40.5	36.5	35.[illegible]
				E_t	psi x 10^6	11.5	10.3	9.[illegible]
				α	in./in./°F x 10^{-6}	10.4	11.8	13.[illegible]
	As Welded	Sheet	0.098	F_{tu}	ksi	31.0	—	27.[illegible]
				F_{ty}	ksi	19.0	—	16.[illegible]
				E_t	psi x 10^6	—	—	—
				α	in./in./°F x 10^{-6}	—	—	—

OPERTIES RECOMMENDED FOR USE IN DESIGN OF ROCKET PROPULSION FLUID SYSTEM COMPONENTS.

(a)	TEST TEMPERATURE										
TS	-320F	-100F	ROOM	200F	400F	600F	800F	1000F	1200F	1500F	1800F
si	—	—	75.0	66.0	58.0	55.0	54.0	48.0	41.0	—	—
si	—	—	30.0	26.0	21.0	19.5	18.5	16.0	12.5	—	—
x 10^6	—	—	29.0	27.9	26.2	24.5	22.9	21.2	19.6	—	—
./°F x 10^{-6}	—	—	8.9	9.3	9.4	9.6	9.9	10.2	10.6	—	—
si	—	—	185.0	160.0	145.0	141.0	140.0	—	—	—	—
si	—	—	147.0	132.0	123.0	119.0	105.0	—	—	—	—
x 10^6	—	—	28.7	28.1	27.0	25.9	24.5	22.8	—	—	—
./°F x 10^{-6}	—	—	—	—	—	—	—	—	—	—	—
si	—	—	220.0	209.0	200.0	196.0	194.0	—	—	—	—
si	—	—	192.0	171.0	158.0	149.0	142.0	—	—	—	—
x 10^6	—	—	28.7	28.1	27.0	25.9	24.5	22.8	—	—	—
./°F x 10^{-6}	—	—	6.1	6.3	6.6	6.8	7.1	7.2	—	—	—
si	—	—	200.0	191.0	184.0	182.0	174.0	—	—	—	—
si	—	—	165.0	150.0	135.0	130.0	119.0	—	—	—	—
x 10^6	—	—	28.7	28.0	27.0	25.9	24.5	22.8	—	—	—
./°F x 10^{-6}	—	—	6.2	6.4	6.6	6.8	7.1	7.2	—	—	—
si	—	—	141.0	119.0	85.0	78.0	73.0	—	—	—	—
si	—	—	54.0	50.0	46.0	44.0	38.0	—	—	—	—
x 10^6	—	—	—	—	—	—	—	—	—	—	—
n./°F x 10^{-6}	—	—	—	—	—	—	—	—	—	—	—
ksi	—	—	170.0	167.0	163.0	159.0	156.0	155.0	154.0	103.0	27.0
ksi	—	—	130.0	126.0	124.0	122.0	121.0	120.0	119.0	90.0	23.0
x 10^6	—	—	31.0	30.5	29.7	28.7	27.5	26.0	23.9	19.7	14.3
n./°F x 10^{-6}	—	—	—	6.6	6.8	7.0	7.2	7.5	7.8	8.4	9.2
ksi	—	143.0	130.0	125.0	117.0	114.0	111.0	110.0	105.0	94.0	—
ksi	—	95.0	85.0	80.0	76.0	74.0	73.0	72.0	80.0	75.0	—
x 10^6	—	—	—	—	—	—	—	—	—	—	—
n./°F x 10^{-6}	—	—	—	—	—	—	—	—	—	—	—
ksi	—	—	121.0	115.0	110.0	105.0	101.0	99.3	97.2	69.0	31.7
ksi	—	—	57.8	54.0	51.0	48.0	46.0	43.9	43.0	40.0	18.2
x 10^6	—	—	29.8	29.0	28.5	27.7	27.0	25.5	24.5	21.2	15.0
n./°F x 10^{-6}	—	—	6.0	6.3	6.7	7.0	7.3	7.5	7.7	8.0	8.5
ksi	56.0	46.0	42.0	38.5	25.0	7.0	—	—	—	—	—
ksi	40.5	36.5	35.0	32.0	21.0	3.5	—	—	—	—	—
x 10^6	11.5	10.3	9.9	9.7	8.9	6.9	—	—	—	—	—
in./°F x 10^{-6}	10.4	11.8	13.1	13.1	13.6	14.1	—	—	—	—	—
ksi	31.0	—	27.0	25.0	—	—	—	—	—	—	—
ksi	19.0	—	16.0	16.0	—	—	—	—	—	—	—
x 10^6	—	—	—	—	—	—	—	—	—	—	—
in./°F x 10^{-6}	—	—	—	—	—	—	—	—	—	—	—

NOTES:

(a) Explanation of Property Symbols:

F_{tu} = Ultimate tensile strength

F_{ty} = Tensile yield strength (0.2% offset)

E_t = Modulus of elasticity (tension)

α = Coefficient of linear thermal expansion (from room temperature to temperature noted)

(b) Hastelloy C data from Reference (19), most other material property data from Reference (18).

(c) As Welded or As Brazed properties for AM 355 stainless steel may also be used for AM 350 stainless steel.

2

The rocket propulsion fluid systems for which the factor of high temperature creep of materials is considered to present a problem are the pneumatic hot gas systems. The mechanical properties of alloys such as may be used for tubing and fittings for these systems are affected by the metallurgical changes which take place in these materials under the influence of elevated temperature and time. These changes are in many cases subject to definite physical laws. These laws generally follow a rate process equation, and from this basis several types of "parameters" have been developed which utilize the principle of some form of time-temperature relationship to enable long-time changes to be predicted from the results of relatively short-time tests. These parameters describe the rate effects, or changes in material properties, as a function of stress. One such widely used parameter is the Larson-Miller Parameter, which will be used for the presentation of creep-rupture properties of materials which may be used in the fabrication of pneumatic hot gas systems.

The Larson-Miller Parameter gives the following relationship for the effects of time and temperature on the creep-rupture properties of materials:

$$P = f(\sigma) = (T + 460)(\log t + C) \qquad [1]$$

where:

P = the Larson-Miller Parameter

σ = stress, psi

T = temperature, degrees Fahrenheit

t = rupture life, hours

C = a Constant

In the relationship shown by the above equation, a constant-stress plot of $\log t$ against the quantity $\frac{1}{(T+460)}$ should produce a series of straight line converging to a single point when $\frac{1}{(T+460)}$ is zero. At this point, $\log t$ is equal to C, and this value of C is theoretically the best Constant to use for the data involved. A value of 20 is frequently used for the Constant C in the Larson-Miller Parameter equation and has given satisfactory results, Reference (20). When enough experimental data are available, a derived value for the Constant C is used.

Creep-rupture properties for the candidate materials are given in Figure 1 in terms of the Larson-Miller Parameter in order to permit extrapolation of the data in terms of the effects of both temperature and time.

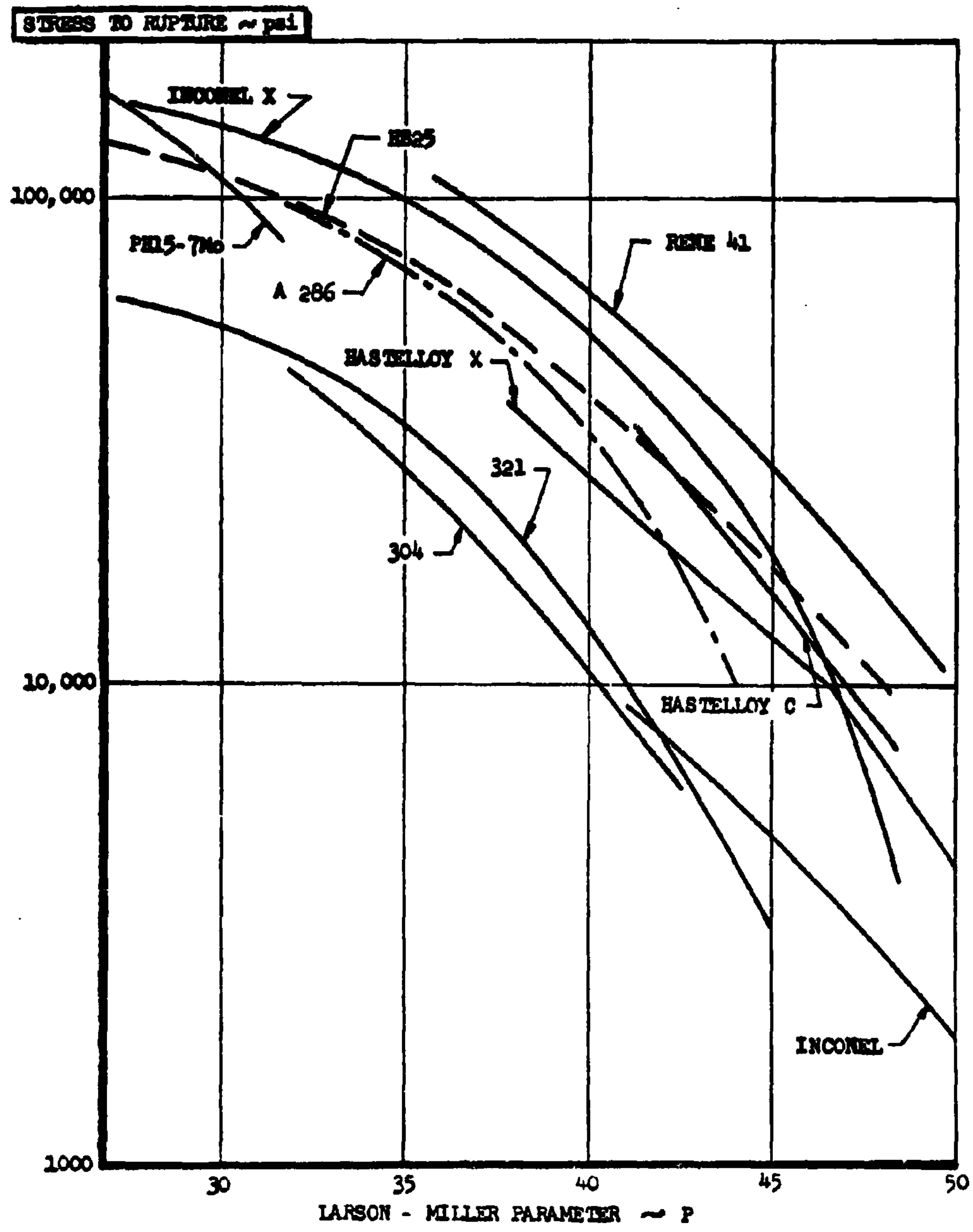


Figure 1 - Creep Rupture Properties of Selected Alloys

Strength Properties of Brazing Alloys

Candidate brazing alloys were selected for investigation under this program on the basis of brazing characteristics such as wettability and flow, on their compatibility with the alloys to be joined, their chemical compatibility with the system fluids, and their strength characteristics. The brazing characteristics and their compatibility with the alloys to be joined will be discussed later in this report in the section on BRAZING. Such data as were available from the literature survey on chemical compatibility have been discussed in the previous paragraphs. The strength properties of the candidate brazing alloys and the determination of shear strength values for use in the design of brazed tubing joints will be discussed in the following paragraphs.

The strength characteristics of the candidate brazing alloys were evaluated on the basis of their block shear strength. The block shear test method for evaluation of braze alloy strength has been established as a reliable, rapid and inexpensive method of joint strength evaluation for use at room temperature, sub-zero and elevated temperatures. A strength relationship has been found to exist between brazing alloys of similar base alloy compositions. Therefore, the block shear strength properties of the candidate brazing alloys can be determined on the basis of only a limited number of tests.

Specimen size is reasonably flexible, and a number of block shear test specimens can be cut from a single larger brazed joint section. Two sizes of test specimens were used for the block shear tests of this investigation. The room temperature test specimens were made by brazing together two pieces of the tubing system material, each 7/16 x 7/16 x 1/2 inch in size, butted together with the brazing alloy between them. The specimens for elevated temperature testing were made by brazing together two pieces of tubing system material, each 1/8 x 7/16 x 1/4 inch in size. The joint was brazed by induction heating in an argon atmosphere as shown in Figure 2, after which the brazed joint section was cut into block shear test specimens of the sizes shown in Figure 3.

A complete screening program to determine the characteristics of a variety of braze alloy compositions has been conducted by the NAA/LAD Metallic Materials Laboratory during the past few years. The evaluation has included block shear tests at temperatures from ambient to 1000 F. The silver-base braze alloys and several of the gold-base braze alloys being considered for use under this program were investigated at that time. The results of previous tests on alloys of interest to this rocket fitting development program have been correlated, and the results are presented in Figures 3 and 4, along with the test values which were determined under this current USAF program

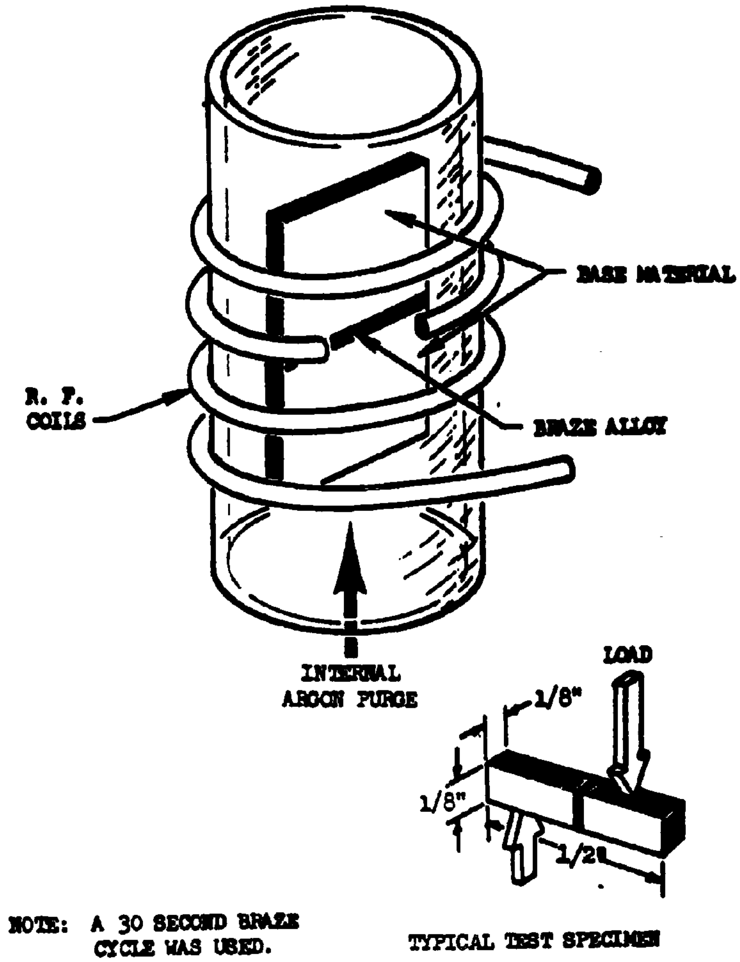


Figure 2. Induction Brazing Setup for Block Shear Specimen Fabrication.

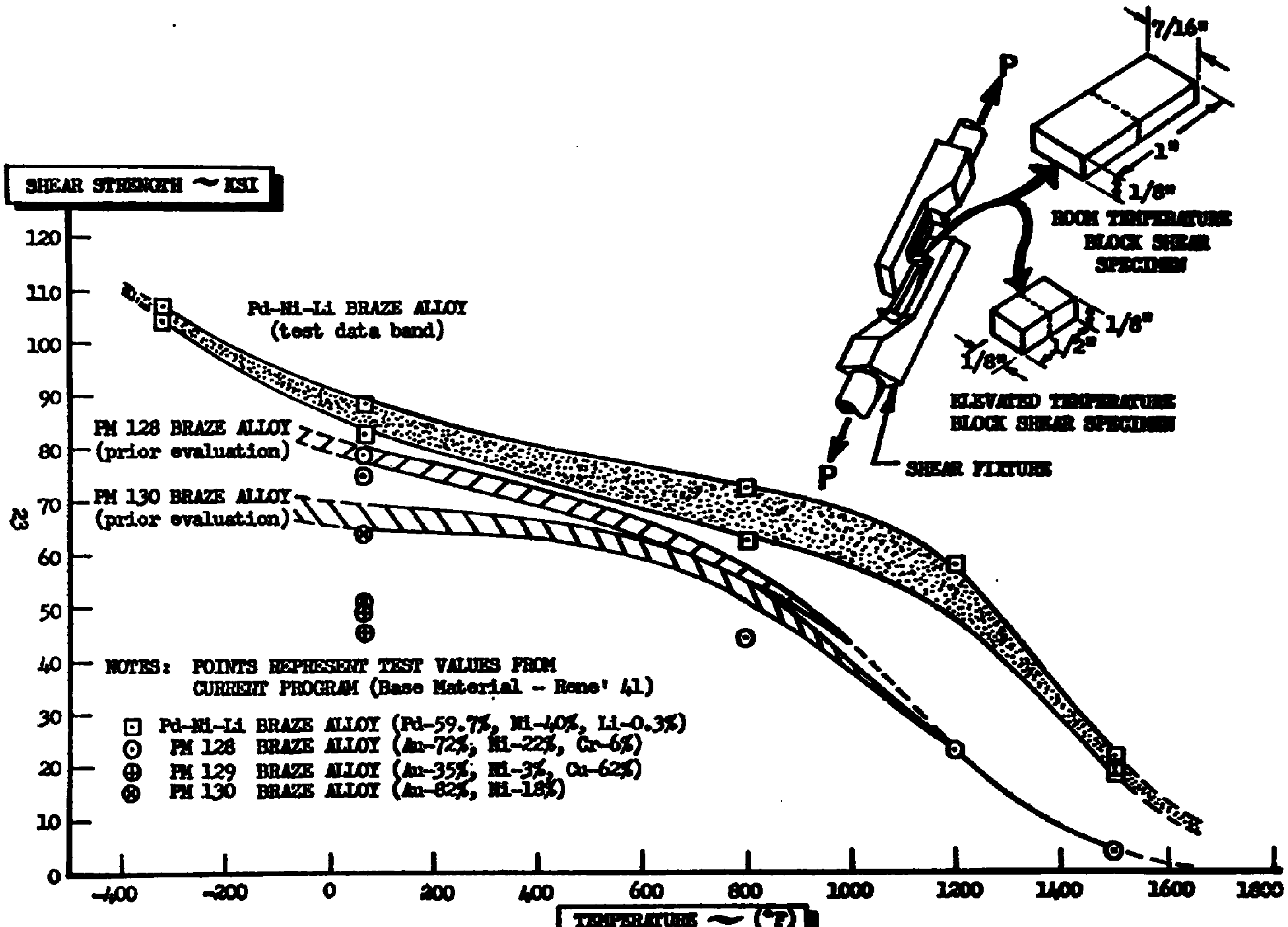


Figure 3. Block Shear Strength Vs. Temperature for Palladium-Nickel-Lithium and Gold-Nickel Base Braze Alloys. Correlation of Data from NAA Tests.

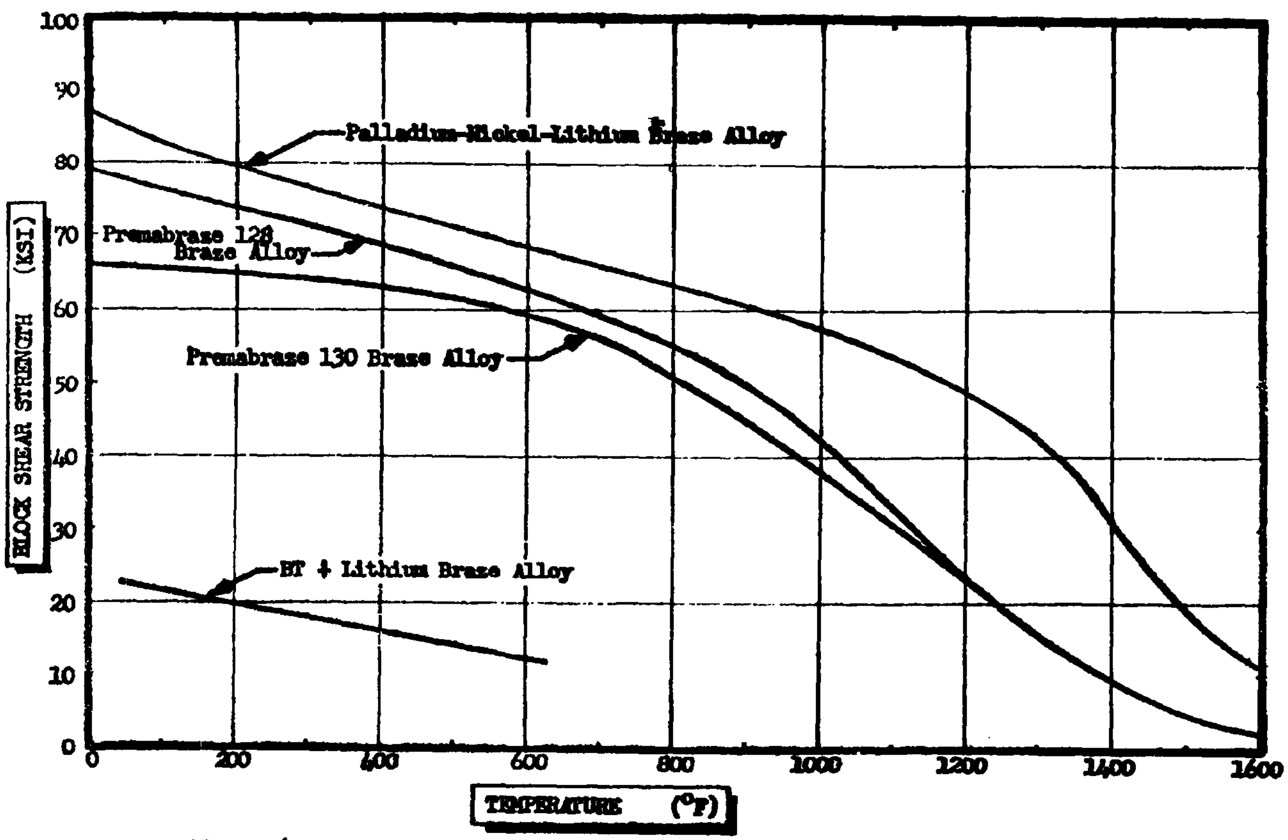


Figure 4. Block Shear Strength Vs. Temperature Properties of Braze Alloys for Use in Design of Tube Joints for Rocket Propulsion Fluid Systems.

Block shear strength tests were performed at temperatures from -320 F to 1500 F. Rene'41 alloy specimens with Palladium-Nickel braze alloy joints were evaluated over the entire temperature range. The results of these tests are presented in Figures 3 and 4, and in Table VIII. This braze alloy exhibited the highest block shear strength properties of the brazing alloys being considered for use in this program.

The gold-base brazing alloys were also evaluated with Rene'41 alloy block shear specimens. The gold-nickel-chromium alloy Premabraze 128 was tested at temperatures from ambient to 1500 F. Two other gold-base brazing alloys, the gold-copper-nickel alloy Premabraze 129 and the gold-nickel eutectic alloy Premabraze 130, were tested only at ambient temperature during the present investigation. Premabraze alloy 130 had been tested at elevated temperatures during the earlier NAA brazing alloy screening programs. The results from all the block shear tests of the gold-base brazing alloys are shown in Figures 3 and 4. The data from the tests conducted on the gold-base brazing alloys during Phase I of the present program are shown in Table IX.

Block shear strength tests were not conducted for the Nicrobraze alloys because the poor performance of these alloys in the preliminary wetting and flow tests (to be discussed under BRAZING) eliminated them from further consideration for brazing Rene'41 tubing. Premabraze alloys 128 and 130, and the 60Pd-40Ni-0.3Li alloy were selected for further evaluation for brazing Rene'41 tube joints.

The block shear strength of Type 347 stainless steel joints brazed with the BT + Lithium alloy, and also of AM 350 stainless steel joints brazed with BT + Lithium alloy, were not determined under this program. Such joints had been fully tested by NAA under previous screening programs. Therefore, the block shear strength values for such joints shown in Figure 4 are taken from the material property values used by NAA for design purposes, Reference 18.

2.3 AVAILABILITY AND WORKABILITY OF TUBE AND FITTING MATERIALS

The factor of availability of a material in the form of tubing and the workability of the material are to a large extent interdependent. Easily worked materials can be formed into all sizes of tubing; but only limited tubing sizes and wall thicknesses can be made from material that is difficult to work.

Tubular shapes are produced by two main processes. Seamless tubing is made by drawing pierced billets or tubular extrusions over mandrels. Welded tubing is produced by forming suitably sized strips into a tubular shape and then welding the edges together. This tubing can be used in the as-welded condition, or it can be redrawn after welding to produce a uniformly sized product with the weld area reworked and smoothed. Tubing which has been welded and cold redrawn, known as "welded and drawn" tubing, is generally considered to be equivalent to seamless tubing.

A great many alloys can be produced in seamless tubular shapes on an experimental basis. Commercially available candidate alloys which can be procured in the form of seamless tubing include the type 300 series austenitic stainless steels, many of the Hastelloy type alloys, Inconel and Inconel X,

TABLE VIII. BLOCK SHEAR STRENGTH EVALUATION

60Pd-40Ni-0.3Li BRAZE ALLOY

SPECIMEN No.	JOINT AREA (sq. in.)	TEST TEMP.	ULTIMATE LOAD (lb)	ULTIMATE SHEAR STRENGTH (psi)	AVERAGE SHEAR STRENGTH (psi)
21 22A	.0143 .0121	-320 F	1495 1290	104,545 106,611	105,500
2 3	.0495 .0454	Room	4100 4025	82,828 88,656	85,700
15 15A	.0198 .0220	800 F	1390 1385	72,202 62,954	67,500
1A	.0208	1200 F	1195	57,451	57,450
13A 13B 14A	.0191 .0173 .0191	1500 F	360 375 362	18,324 21,675 18,905	19,900

Note: Base Material - Rene' 41

Braze area appeared void free.

TABLE IX. BLOCK SHEAR STRENGTH EVALUATION

GOLD-BASE BRAZE ALLOYS

SPECIMEN No.	JOINT AREA (sq.in.)	TEST TEMP.	ULTIMATE LOAD (lb)	ULTIMATE SHEAR STRENGTH (psi)	VOIDS IN JOINT AREA (Percent)	CORRECTED ALLOY SHEAR STRENGTH* (psi)	AVERAGE SHEAR STRENGTH (psi)
			Premabraze 128 Alloy				
7	.0488	Room	3480	71,311	5	74,876	76,700
8	.0521		3410	65,451	20	78,541	
16A	.0154	800 F	676	43,895	0	43,895	43,895
16	.0153	1200 F	330	21,700	5	22,800	22,800
9	.0193	1500 F	59	3,056	20	3,820	3,820
			Premabraze 129 Alloy				
4	.0464	Room	2285	49,245	0	49,245	47,200
5	.0424		1825	43,042	5	45,194	
			Premabraze 130 Alloy				
11	.0449	Room	2100	46,770	10	51,447	57,700
12	.0504		3070	60,912	5	63,957	

Note: Base Material - Rene' 41

*Shear strength values are corrected for void areas.

aluminum and most of the aluminum alloys, and tantalum. Welded and drawn tubing can be produced in a wider variety of alloys, including AM 350 stainless steel and Rene' 41 alloy.

The delivery time of tubing made from many of the special alloys, such as Rene' 41, depends of course on the dimensional size and on the amount ordered. Medium quantity lots can, in general, be supplied more economically and more quickly than very small or very large orders. Non-standard sizes are very difficult to obtain, and the manufacture of special dies would be warranted only for very large quantity orders. The small quantities usually required for experimental purposes frequently can be obtained only by accepting overruns or extras left over from prior productions lots. However, in the case of some materials, such as the type 300 stainless steels, just about any size and wall thickness is available from warehouse stock.

2.4 MACHINABILITY OF FITTING MATERIALS

The fittings which are used to make the connections between the system tubing are in the form of short sleeves. The sleeves for the welded joints are usually made by expanding short lengths of tubing an appropriate amount. The sleeves for the brazed joints must be machined to obtain the required dimensions and precision tolerances required for the bore and the brazing alloy grooves. The brazing sleeves are usually machined from tube or solid bar.

Machinability is generally a function of strength and the strain hardenability of a material. Some measure of the machinability of a material can be obtained from an overall machinability rating. This rating is derived experimentally by the force and power required to remove a given amount of material in a given time by various machining processes. The ratings are compared to a value of 100 for a free-machining steel. The following machinability ratings for some candidate alloys are based on data from the technical literature and also from tests conducted in the experimental machine shops at North American Aviation, Inc.

Candidate Material	Relative Machinability Rating
Type 316 stainless steel	50
Type 321 stainless steel	50
Type 347 stainless steel	50
Inconel	40
Inconel X	20
Waspalloy	20
Rene'41	15
Titanium & Titanium Alloys	30 - 60
Aluminum & Aluminum Alloys	100 - 200

2.5 CONCLUSIONS ON MATERIALS SELECTION

Of all the candidate materials for rocket propulsion fluid system tubing and fittings, titanium alloys have the best strength-to-weight ratio. However, titanium and its alloys have a very low chemical compatibility with many rocket propulsion system fluids and due to the many fabrication problems their use is not recommended.

Stainless steels of the type 300 series austenitic steels have a low yield strength, particularly at elevated temperatures. Nevertheless, their strength at room temperature is reasonable, and they have quite good strength at low temperatures. The general chemical compatibility of these stainless steels with the rocket propulsion system fluids is good. In addition, they are readily available in the required sizes for use in rocket fluid systems. Of all the type 300 series stainless steels, type 347 appears to have the best chemical compatibility with all of the rocket system fluids except fluorine. Type 347 stainless steel is recommended for service from cryogenic temperatures up to temperatures in the range from 200 F to 600 F.

Aluminum alloys have some promise for low temperature service, but the difficulties encountered in joining them by the welding and brazing techniques of this program, as well as their generally low standard of chemical compatibility have caused them to be virtually eliminated as candidate materials for consideration in this program.

The potential candidate materials for elevated temperature service are tantalum and a group of heat-resisting superalloys consisting of the Hastelloys, Waspalloy, Inconel 718, and Rene' 41. Rene' 41 has been selected from the latter group for several reasons. It has a greater potential chemical compatibility with the rocket system fluids than do the other materials in the group, notably the Hastelloys. Rene' 41 is also more readily available in the form of tubing than are some of the other materials at the present time. Finally, Rene' 41 in the "as welded" and "as brazed" conditions has satisfactory strength for use in this program, and responds rapidly to aging at elevated temperatures, thus recovering much of the strength lost in joining. Inconel 718 was found to have extremely low strength in the annealed and the "as welded" conditions. Inconel 718 is reported to be very sluggish in its aging response, and thus would take a long time to recover the strength lost during the joining process. Tantalum would be a very suitable material from the point of view of chemical compatibility, but its cost is so high as to preclude widespread use except in cases where no other material would be suitable.

One other material has been selected for testing at elevated temperatures under this program along with the Type 347 stainless steel and the superalloy Rene' 41. This is the precipitation hardening stainless steel AM 350. AM 350 has been selected because of its generally good chemical compatibility and its excellent strength-to-weight ratio. This material is, therefore, recommended for inclusion in this program. The fittings, or sleeves, for the welded joints in AM 350 tubing systems are made by expanding short lengths of the tubing to be joined. The brazing fittings are machined from AM 355 stainless steel bar stock.

It is believed that the materials selected for development and testing as fittings under this program, while not in common usage for rocket propulsion fluid systems at the present time, all show promise for such application in the near future. Results obtained with these materials should be capable of being extrapolated to other service conditions to a useful extent.

3. STRUCTURAL ANALYSIS

3.0 GENERAL REQUIREMENTS

The components of rocket fluid systems for which a stress analysis is to be conducted under this program are the tubing lines and the fittings, or joining sleeves. Joining techniques to be considered are the brazing and the welding processes. The environment to be dealt with consists of high internal pressures, and also intensive heating and cooling which causes a sharp thermal gradient across the tube or fitting wall.

For engineering purposes the analysis is made in accordance with the following considerations:

(1) The tubes are treated as thick shells subject to both high radial temperature variation and internal pressure.

(2) The loads are rotationally symmetrical about the axis of rotation.

(3) The principle of superposition operates within the elastic range; that is, the elastic and thermal stresses can be combined algebraically.

3.1 TUBING ANALYSIS

The following equation governing the distribution of stresses in a tube are used for tubing stress analyses. The derivation of these equations are shown in Reference (21).

The maximum circumferential, or hoop, stress is:

$$(\sigma_\theta)_{max} = \frac{b^2 + a^2}{b^2 - a^2} p_i \qquad [1]$$

where:

a = inside diameter of tubing

b = outside diameter of tubing

p_i = internal (system) pressure

Thermal stresses are produced in the tubing by the temperature difference between the inner and outer surfaces of the tubing wall. These thermal stresses can be calculated by the following equation:

$$\sigma_t = \pm \frac{\alpha E (T_i - T_o)}{2(1-\mu)} \qquad [2]$$

where: α = linear coefficient of thermal expansion of tubing material

T_i = temperature on inner surface of tube wall

T_o = temperature on outer surface of tube wall

μ = Poisson's ratio of tubing material

The upper sign of the $\pm$ sign in Equation [2] applies to the thermal stress at the outer surface of the tube wall, and the lower sign to the thermal stress at the inner surface. When the temperature of the tube wall inner surface is less than that of the tube wall outer surface ($T_i < T_o$), the outer surface thermal induced stress is compressive and the inner surface thermal stress is tensile, References (21) and (22).

The principle of superposition can be used to combine the thermal induced stresses on the tubing wall with the stresses produced by the internal pressure in the tube in order to determine the critical stress in the tubing and its location. In the case noted above, where the tube wall outer surface is hotter than the inner surface, the critical combined stress is a tension stress on the inner surface. Where the thermal gradient is large, the critical combined stress can reach the yield strength of the material as a limiting value. The redistribution of local stresses should be considered, especially during equilibrium heating conditions, References (23) and (24).

If the wall thickness of the tubing is defined by $b/a \leq 1.5$, and the maximum circumferential stress, $(\sigma_\theta)_{max}$, is defined as the material yield strength, F_{ty}, for the proof loading condition or the tensile ultimate strength, F_{tu}, for the burst condition; by Reference (25), Equation [1] can be used to calculate the tube wall thickness required for a given internal pressure and temperature environmental condition. The following equation, which is derived from Equation [1], can be used to calculate the wall thickness:

$$t = \left(\frac{D}{2}\right)\left(1 - \sqrt{\frac{F_t - P_i}{F_t + P_i}}\right) \qquad [3]$$

where: $t = b - a$

D = nominal tube diameter

F_t = material yield (proof) or ultimate (burst) strength

The material strengths, F_{tu} and F_{ty} , are temperature dependent. Therefore, the material strength values for the maximum service temperature, as shown in Table VII, should be used in the calculation of the tubing wall thickness. The use of the short-time high temperature strength values is satisfactory for rocket systems where the time at temperature and under load is relatively short. For systems where the tubing may be under load at high temperatures for more than one or two hours total time, the creep strength values shown in Figure 1 should be used.

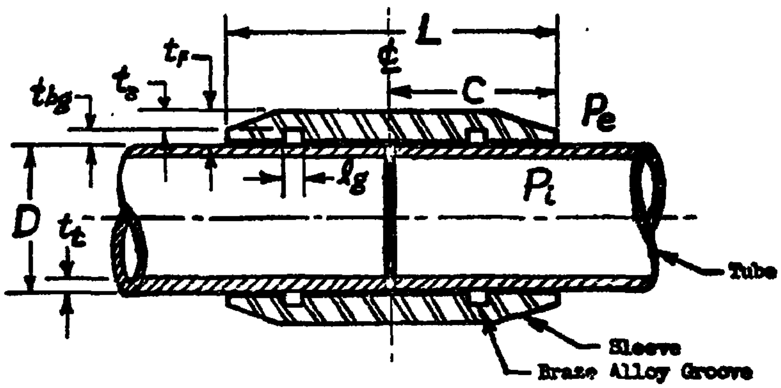
The theoretical value for tube wall thickness calculated by use of Equation [3] should be increased by ten percent to compensate for the effects of minor material imperfections and other factors which might reduce the tubing strength or adversely affect the service life. Finally, the actual wall thickness specified should be a standard size for the particular tubing material. If the calculated size is between two standard sizes, the heavier, or thicker, size should be specified.

3.2 FITTING (SLEEVE) ANALYSIS

Wall Thickness

The wall thickness specified for the fittings, or sleeves, for the welded tube connections is normally the same as the wall thickness of the tubes being joined. In most cases, the weld joint sleeve fitting will be made by expanding the diameter of a short length of the same tubing just enough so that it can be slipped over the tubing. The procedures and tolerances for this will be further discussed in the section on the weld joining process.

The wall thickness of the braze joint fittings, or sleeves, must be greater than that of the weld fittings in order to provide for the internal circumferential grooves required to hold the brazing alloy. In order to provide for the stress concentration due to the brazing alloy grooves and for other imperfections, the material strength allowable used as F_t in Equation [3] should be 2/3 of the values given in Table VII.



Fitting Length

The length of the weld fitting sleeve is not too critical. The sleeve should be sufficiently long that it can give support to the heat affected zone; that is, the length of the tubing near the weld joint which has been softened by the welding heat. The weld fitting sleeve length will be further discussed in the section on the weld joining process.

The length of the braze fitting sleeve is critical to the strength of the brazed joint. The primary concern is that it withstand the load along the tube axis; that is, the load which tends to pull the tube end out of the sleeve. This load is the result of the stress produced by the internal pressure in the tube, the stresses due to temperature effects on different sections of the piping system, and mechanical effects due to warping of the structure which supports the piping system. However, the axial load cannot exceed the tensile strength, either F_{tu} or F_{ty}, of the tubing itself or the tubing would fail before the joint. The tensile strength of the tubing is given by:

$$\sigma_{axial} = F_t \pi D t_t \qquad [4]$$

The axial strength of the brazed joint is given by:

$$\sigma_{axial} = F_s \pi D (C - N\ell_g) \qquad [5]$$

where:

F_t = tensile F_{tu} or F_{ty} of tube material

F_s = shear strength of brazing alloy

D = nominal diameter of tubing

C = half length of fitting sleeve

ℓ_g = width of braze alloy groove in sleeve

N = number of braze alloy grooves in length C

Since the braze joint need only equal the strength of the tubing, Equations [4] and [5] may be combined to give the half length of the brazed sleeve as:

$$C = \frac{F_t t_t}{F_s} + N\ell_g \qquad [6]$$

and the total length of the brazed fitting sleeve is:

$$L = 2C = \frac{2F_t t_t}{F_s} + 2N\ell_g \qquad [7]$$

In order to distribute the shear stress more evenly along the length of the brazed joint, the ends of the fitting sleeve should be tapered in thickness as shown on the sketch on the preceding page. See Reference (26).

3.3 DETERMINATION OF TUBING SIZES

Based on the foregoing stress analysis procedures, data were prepared in the form of curves showing the relationship between tubing diameters and wall thicknesses for various system pressures and temperatures. The data are presented for 6061 aluminum alloy, AISI Type 347 and AM 350 stainless steels, and Rene' 41 nickel-base alloy tubing. These data are shown on Figures 5 through 9.

The individual tubing sizes which were to be used in the Phase II Qualification Test Program were selected to represent both the minimum and maximum tube sizes normally used in each particular fluid system. The 3 inch diameter size for the AISI Type 347 stainless steel tubing was the largest size propellant tubing for which testing was contractually required, even though fitting connection designs were to be prepared later for larger tubing sizes, as determined to be feasible, up to a maximum of 16 inches diameter.

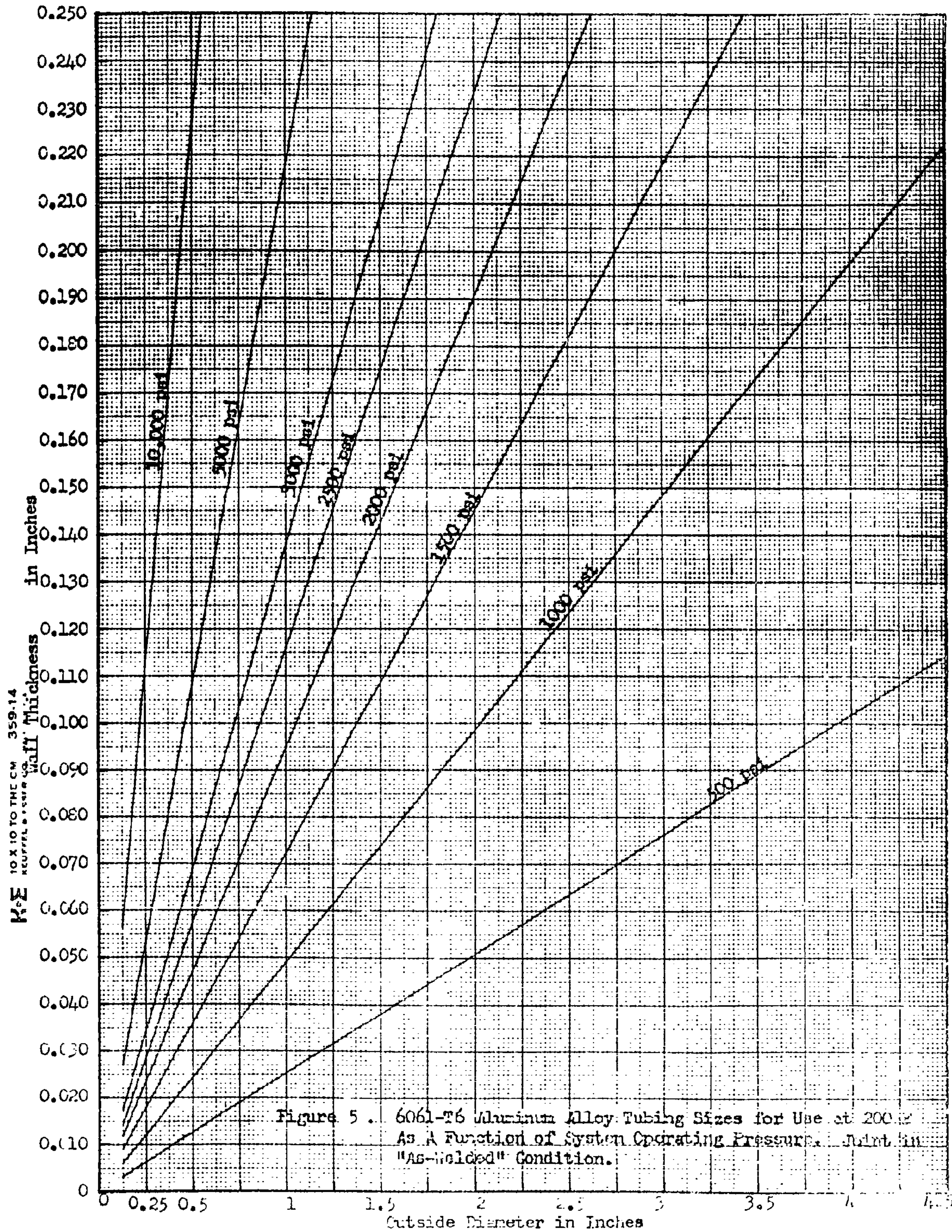


Figure 5. 6061-T6 Aluminum Alloy Tubing Sizes for Use at 200°F As A Function of System Operating Pressure. Joint in "As-Welded" Condition.

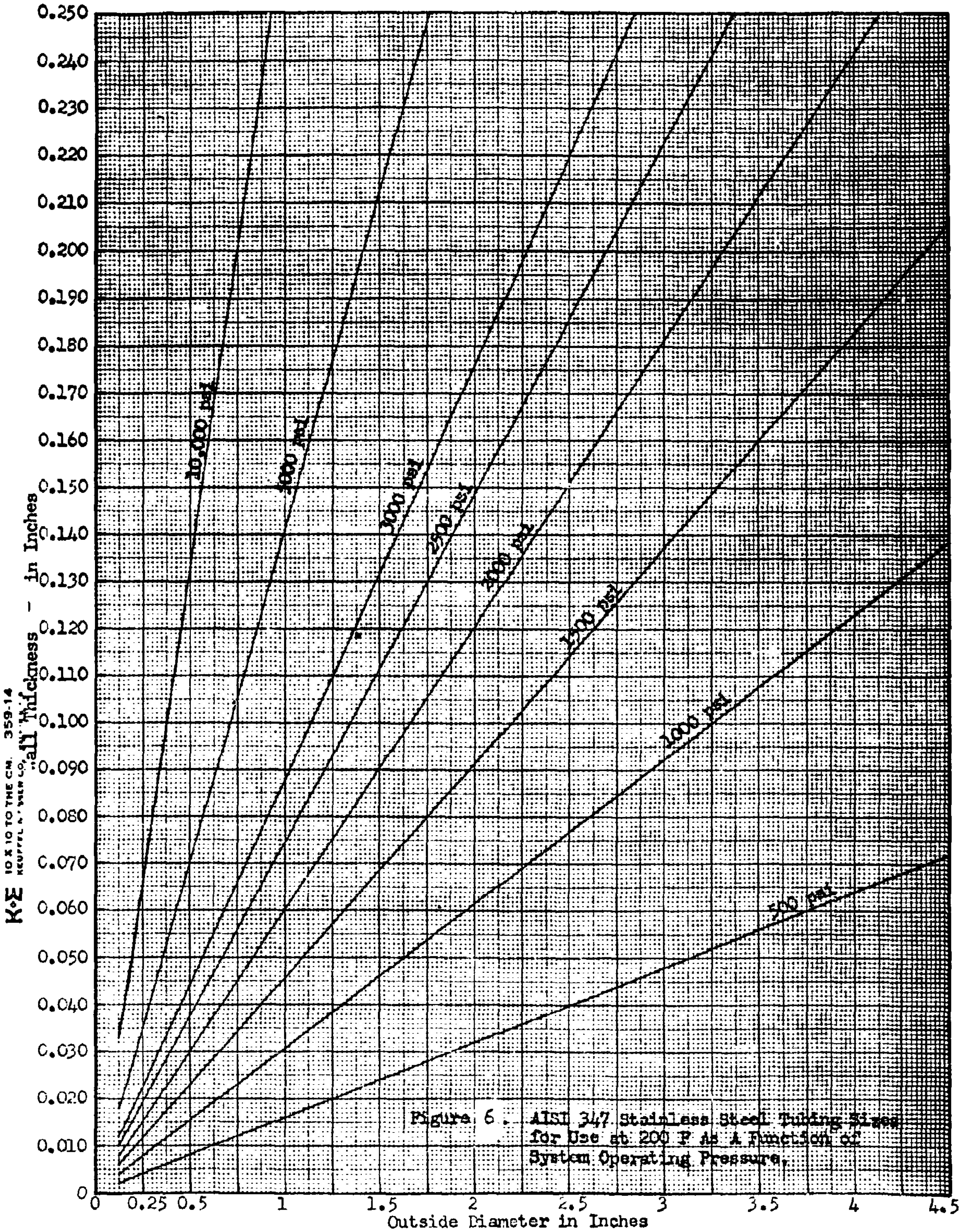


Figure 6. AISI 347 Stainless Steel Tubing Sizes for Use at 200 F As A Function of System Operating Pressure.

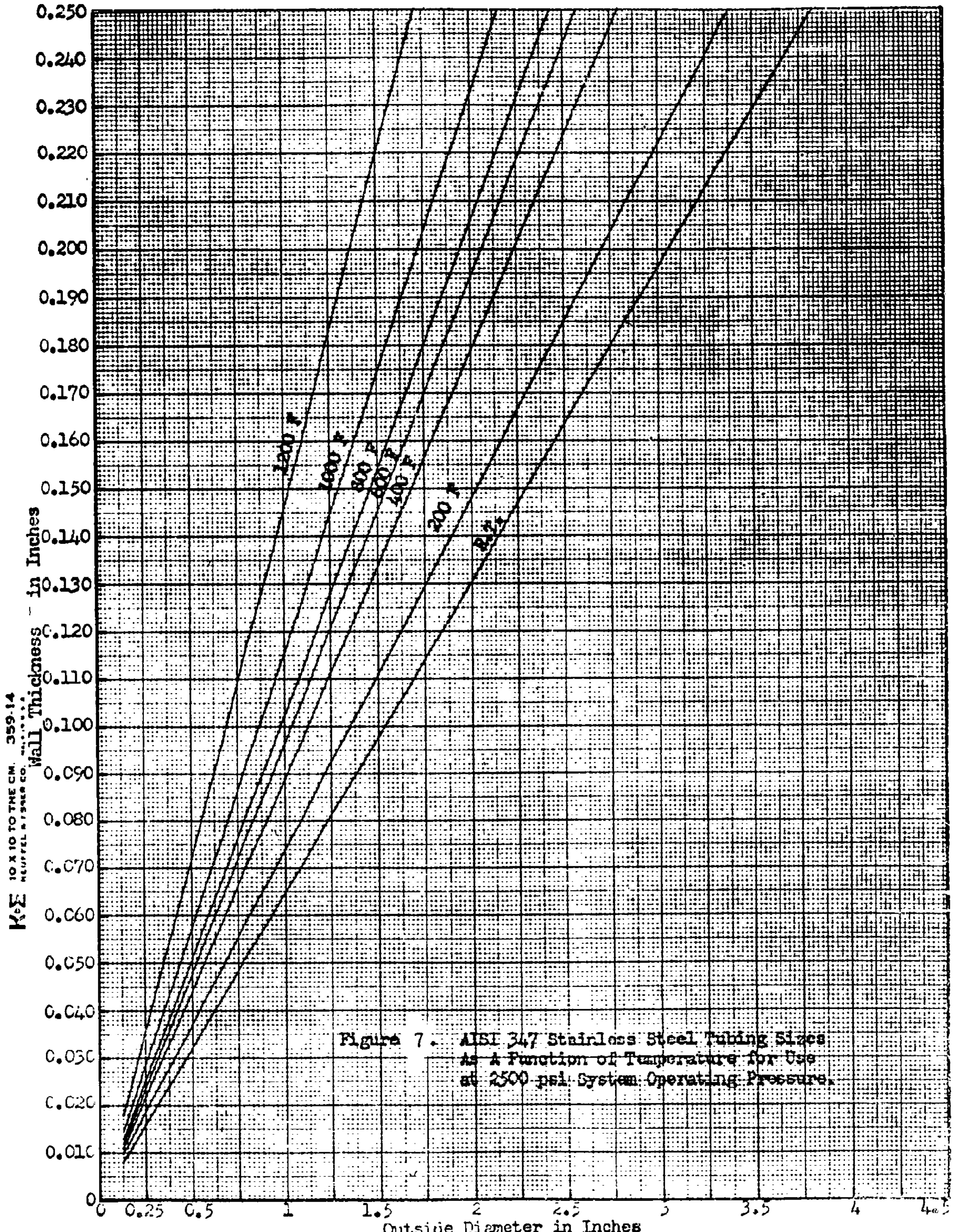


Figure 7. AISI 347 Stainless Steel Tubing Sizes As A Function of Temperature for Use at 2500 psi System Operating Pressure.

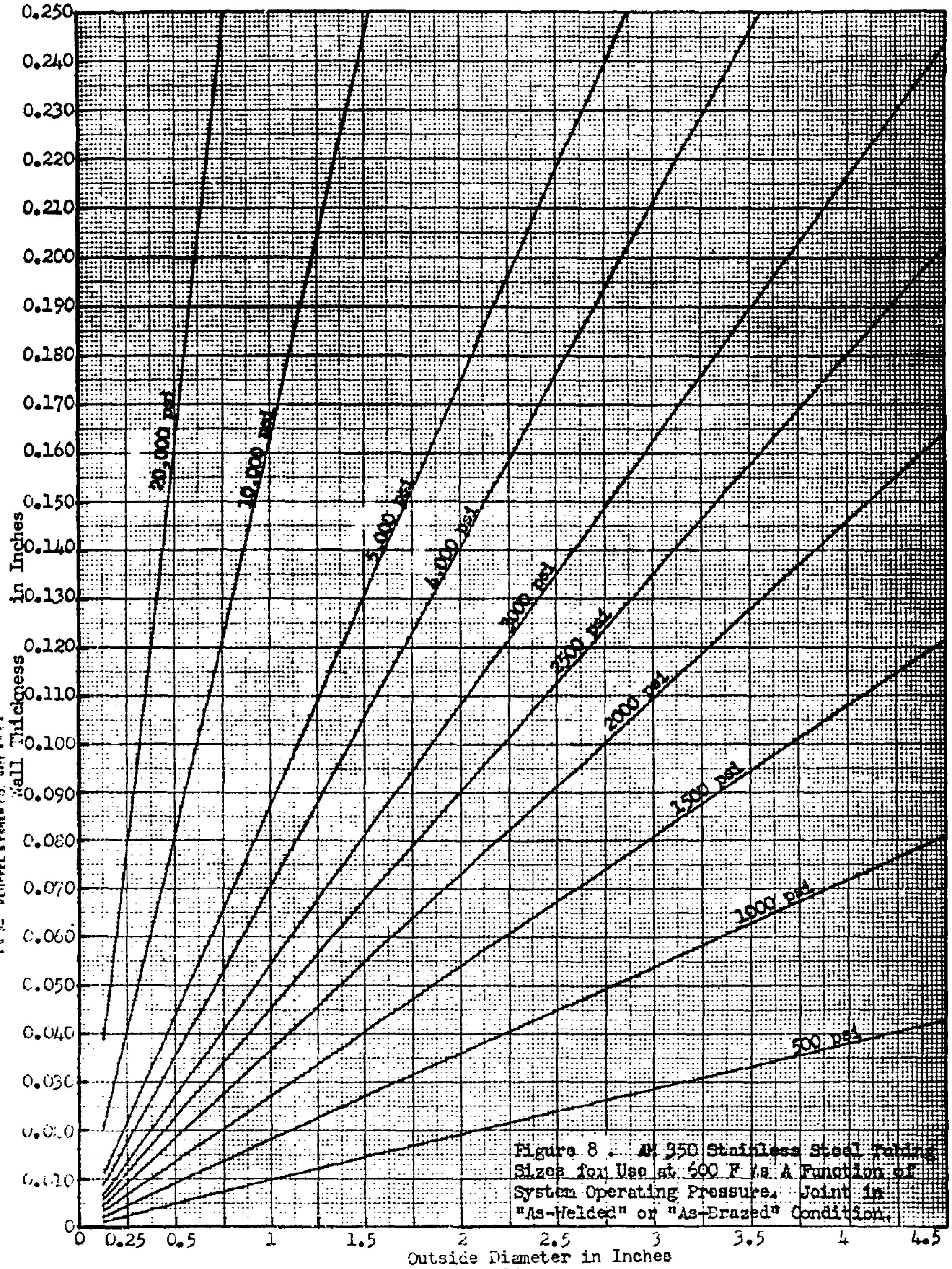


Figure 8 . AM 350 Stainless Steel Tubing Sizes for Use at 600 F As A Function of System Operating Pressure. Joint in "As-Welded" or "As-Brazed" Condition.

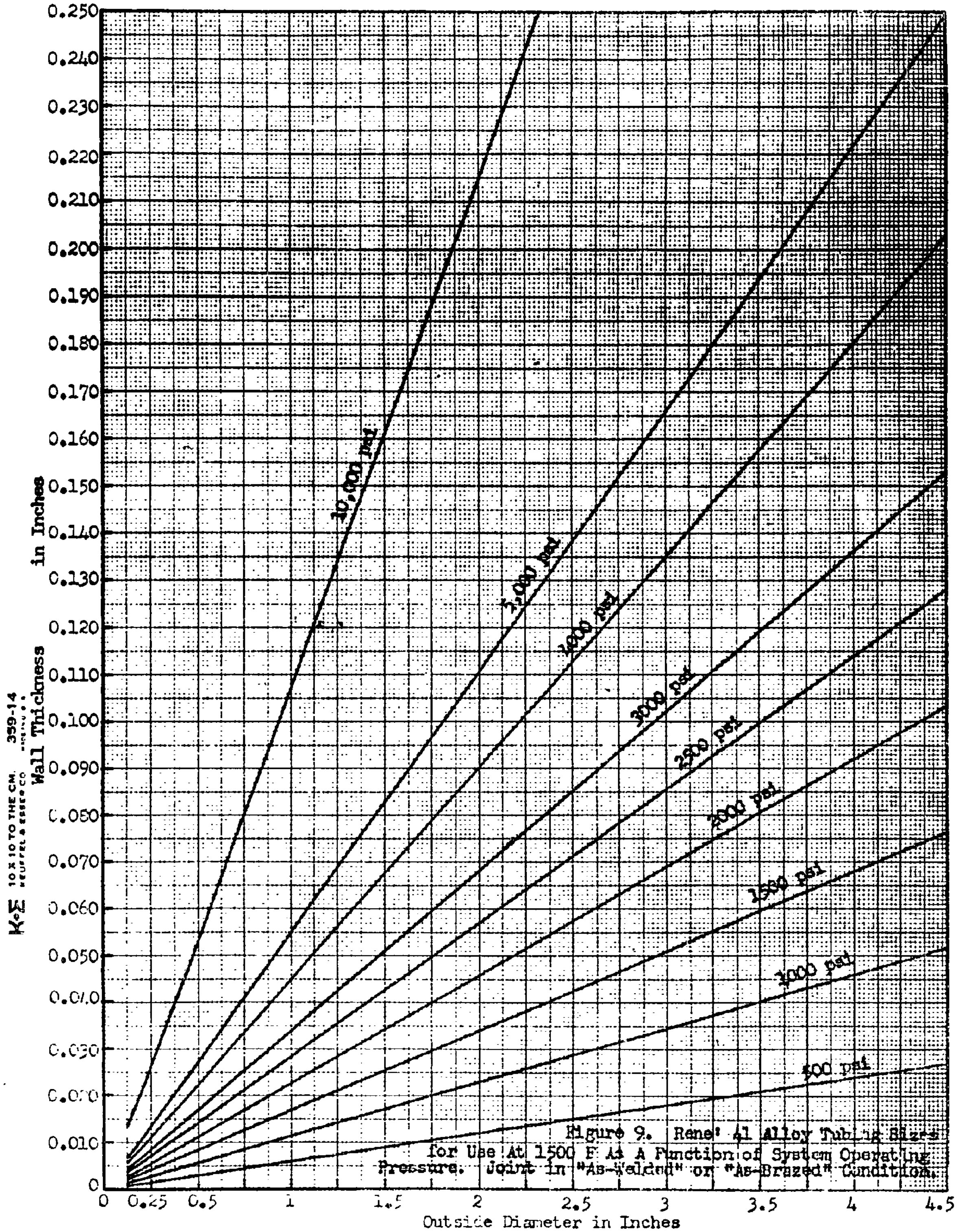


Figure 9. Rene' 41 Alloy Tubing Sizes for Use At 1500 F As A Function of System Operating Pressure. Joint in "As-Welded" or "As-Brazed" Condition.

4. TUBE BRAZING

4.0 GENERAL

The concept of using brazed joints for connecting fluid system lines is not new, but the use of such joints in aircraft and rocket systems has not occurred until very recently. It is only in the last few years that the brazing technology and equipment required for making brazed joints "in place" and under field conditions have become sufficiently well developed. The techniques for making fluid system brazed joints by induction heating at a distance from the power supply were first developed by the Los Angeles Division of North American Aviation, Inc., for use in the construction of the X-15 rocket research vehicle. These techniques and equipment were further developed and improved for use in assembly of the B-70 aircraft. The work reported in this section utilized the previous technology to establish new improved brazing techniques and fittings for use in fluid systems on rocket propulsion vehicles.

4.1 SELECTION OF BRAZING ALLOYS

Prior to selection of brazing alloys for evaluation, a review was made of the literature and of previous work conducted by the Contractor. Based upon this review, the following brazing alloys were selected for use with each of the tubing materials:

TUBE MATERIAL	CANDIDATE BRAZING ALLOY
Type 347 Stainless Steel	BT + Lithium Premabraze 128 Premabraze 130
AM 350 Stainless Steel	BT + Lithium
Rene' 41	Nicrobraz 150 Nicrobraz LM Premabraze 128 Premabraze 129 Premabraze 130 60% Palladium + 40% Nickel + Lithium

The chemical composition of each of these brazing alloys are listed in Table X.

TABLE X. COMPOSITIONS OF CANDIDATE BRAZING ALLOYS

BRAZING ALLOY	CHEMICAL COMPOSITION (Percent)										MELTING TEMPERATURE	BRAZING TEMPERATURE USED
	Au	Ag	Ni	Pd	Cr	Cu	Si	Li	B	Fe		
BT + Lithium	—	71.8	—	—	—	28	—	0.2	-	—	1410 F	1450 F
Premabraze 128	72	—	22	—	6	—	—	—	-	—	1785-1835 F	1950 F
Premabraze 129	35	—	3	—	—	62	—	—	-	—	1787-1886 F	1890 F
Premabraze 130	82	—	18	—	—	—	—	—	-	—	1742 F	1850 F
Microbraz 150	—	—	81.5	—	15	—	—	—	3.5	—	1930 F	2150 F
Microbraz LM	—	—	83.5	—	6	—	5	—	3	2.5	1830 F	1900 F
60Pd-40Ni-0.3Li	—	—	40	59.7	—	—	—	0.3	-	—	2100 F	2150 F

The criteria used for selection of candidate brazing alloys are listed below and are discussed in detail in the following paragraphs:

(1) Wettability

(2) Flow

(3) Compatibility with the base material

(4) Corrosion resistance

(5) Strength

Wettability and Flow

The wetting and flow characteristics of candidate brazing alloys were determined by heating small samples of each of the materials to progressively higher temperatures in an atmosphere controlled tube furnace. Temperature was monitored through thermocouples attached to the back side of the test specimens. After the desired temperature had been reached, and the specimen had stabilized at temperature for a few minutes, it was withdrawn from the hot zone of the furnace and allowed to cool in an inert argon atmosphere.

The wetting and flow characteristics of the braze alloys were evaluated visually. Three typical test specimens which exhibit various degrees of wetting and flow are shown in Figure 10. The wettability and flow characteristics of the selected candidate brazing alloys with the tubing system materials are presented in Table XL. It should be noted that the results of this type of test, although qualitative in nature, do establish the wetting compatibility of the selected materials and also the approximate brazing temperature for the braze alloy-tube material combination.

All the candidate braze alloys selected for use with Type 347 stainless steel have exhibited satisfactory wetting and flow. The BT + lithium alloy appears slightly superior to the Premabraze alloys 128 and 130. This is to be expected since the lithium addition greatly improves wetting and fluidity of the brazing alloy. As noted in a previous section of this report, the block shear strength of the BT + lithium braze alloy was found to be satisfactory for the requirements of the Type 347 stainless steel tubing system. Both the silver-base BT + lithium alloy and the gold-base Premabraze 130 alloy were selected for further evaluation for brazing joints in Type 347 stainless steel tubing.

The BT + lithium alloy was the only candidate brazing alloy considered for use with AM 350 stainless steel. This alloy has proved very satisfactory in use for the B-70 hydraulic system line joints, and has satisfactory wetting, flow, and strength properties for the AM 350 stainless steel tubing system pressure and temperature requirements.

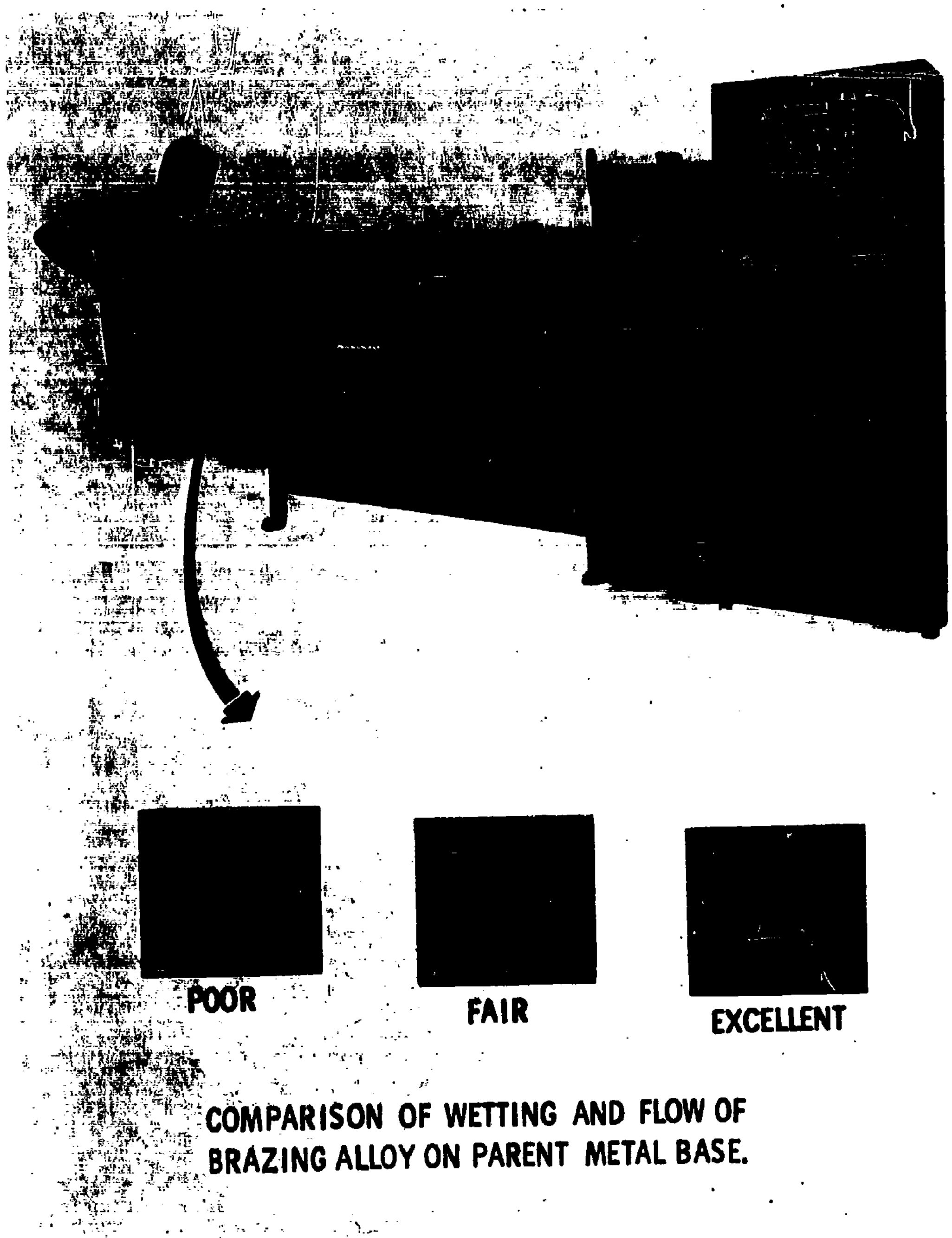


Figure 1[illegible]. Wettability Test of Brazing Alloys

TABLE XI. EVALUATION OF BRAZE ALLOYS

BASE (TUBE) MATERIAL	CANDIDATE BRAZING ALLOY	WETTABILITY	FLOW
AISI 321 or 347 Stainless Steel	BT + Lithium Premabraze 128 Premabraze 130	Good Good Good	Good Fair Fair
AM 350 Stainless Steel	BT + Lithium	Good	Good
Rene' 41	Premabraze 128 Premabraze 129 Premabraze 130 60Pd-40Ni-0.3Li Microbraz 150 Microbraz LM	Good Good Good Good Fair Fair	Fair Fair Fair Good Poor Poor

Premabraze alloys 128, 129 and 130, and the 60Pd-40Ni-0.3Li alloy showed the best wetting and flow properties with Rene' 41 base metal. These braze alloys were then tested for block shear strength as described in a preceding section of this report. Information about the brazing characteristics of the candidate brazing alloys can also be determined during the block shear tests. The extent of melting, wettability and flow of the brazing alloys can be observed from examination of the sheared surfaces of the specimens after testing. The effectiveness of various cleaning procedures can also be evaluated in this manner. Finally, metallurgical examination of the specimens can be performed to determine the extent and type of diffusion or other reaction of the braze alloy with the basis material. The braze alloys used to make the block shear specimens were in the form of foil; the gold-base alloys were .002 inch thick foil, and the palldium-nickel alloy was .005 inch thick foil. The composition, melting temperature, and brazing temperature of these and other candidate brazing alloys considered for this program are given in Table X.

The palladium-nickel brazing alloy exhibited the best consistent wetting and flow characteristics of the braze alloys which were used to make Rene' 41 block shear test specimens for this program. This was judged by the appearance and absence of voids in the failed braze surfaces of the block shear specimens, such as those shown in Figures 11 and 12. The gold-base alloys Premabraze 128, 129 and 130 exhibited a less consistent flow and wetting of the Rene' 41 block shear specimens, as evidenced by the presence of up to 20 percent voids in the failed braze surfaces of some of the tested specimens. The degree of void area for the gold-base alloy specimens is listed in Table XI, and the appearance of the failed surfaces of the specimens tested at room temperature are shown in Figures 13, 14 and 15.

The two Nicrobraz alloys did not show satisfactory wetting and flow characteristics with Rene' 41. Examination of the braze alloy flow specimens indicated that the binder used in these powder alloys adversely affected the wetting and flow of the alloys. As previously noted, block shear strength tests were not conducted for the Nicrobraz alloys.

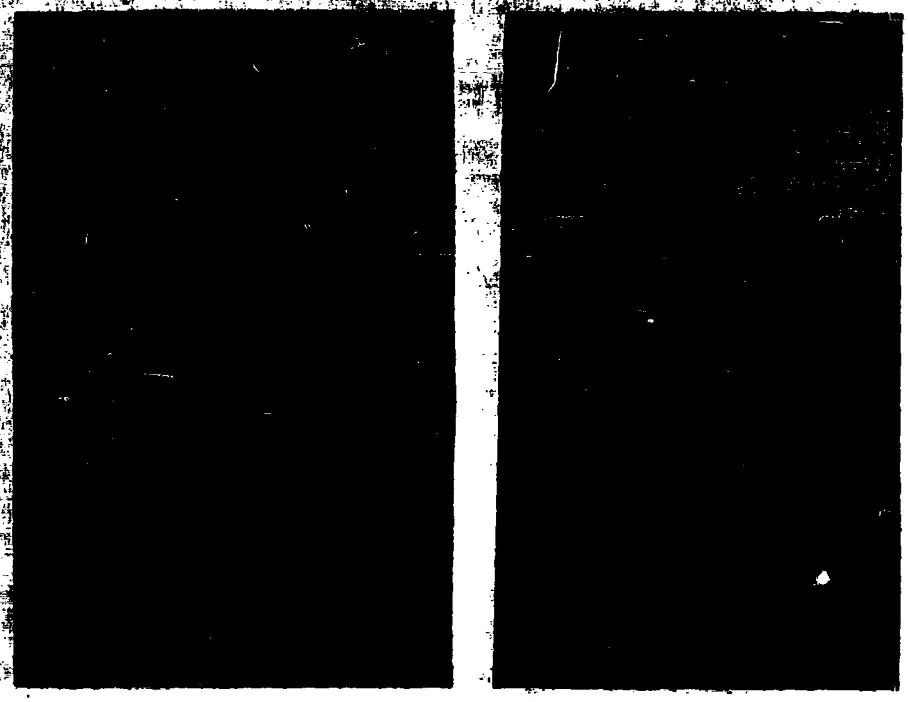
On the basis of the wetting, flow, and block shear strength tests, Premabraze alloys 128 and 130, and the 60Pd-40Ni-0.3Li alloy were selected for further evaluation for Rene' 41 tube joint brazing.

4.2 BRAZING PARAMETERS

The following brazing parameters were considered essential for successful tube brazing. These parameters were studied in detail for each of the tubing materials considered for use in this program.

(1) Cleaning
(2) Atmosphere control
(3) Fitting (sleeve) design
(4) Induction heating coil design
(5) Heating rate and uniformity of heating

Three other factors also considered important were the form of the brazing alloy, the diametrical spacing between the fitting (sleeve) and the tube, and the power requirements for brazing.



Magnification - 10X

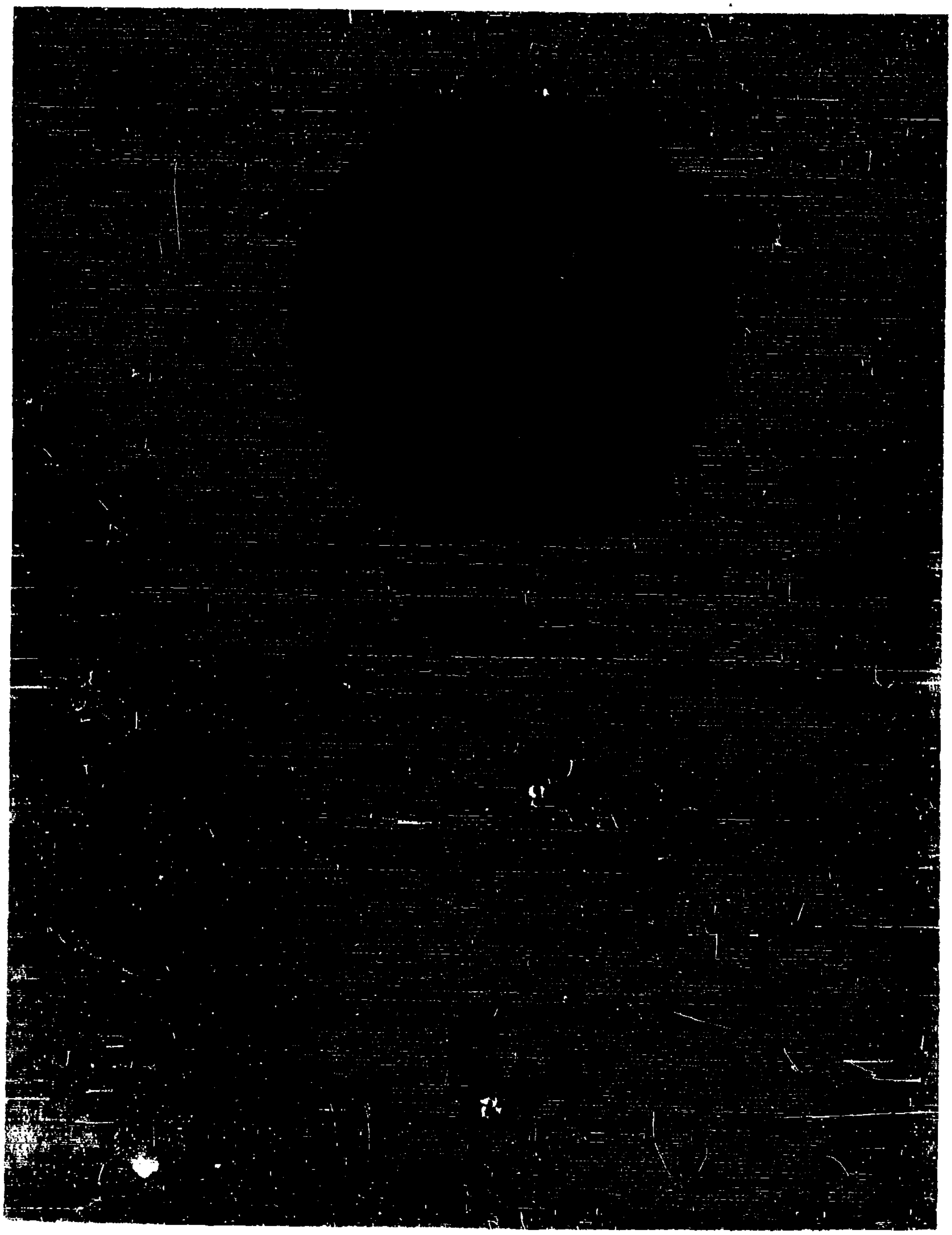
Specimen No. 2
Ultimate Strength 82,828 psi

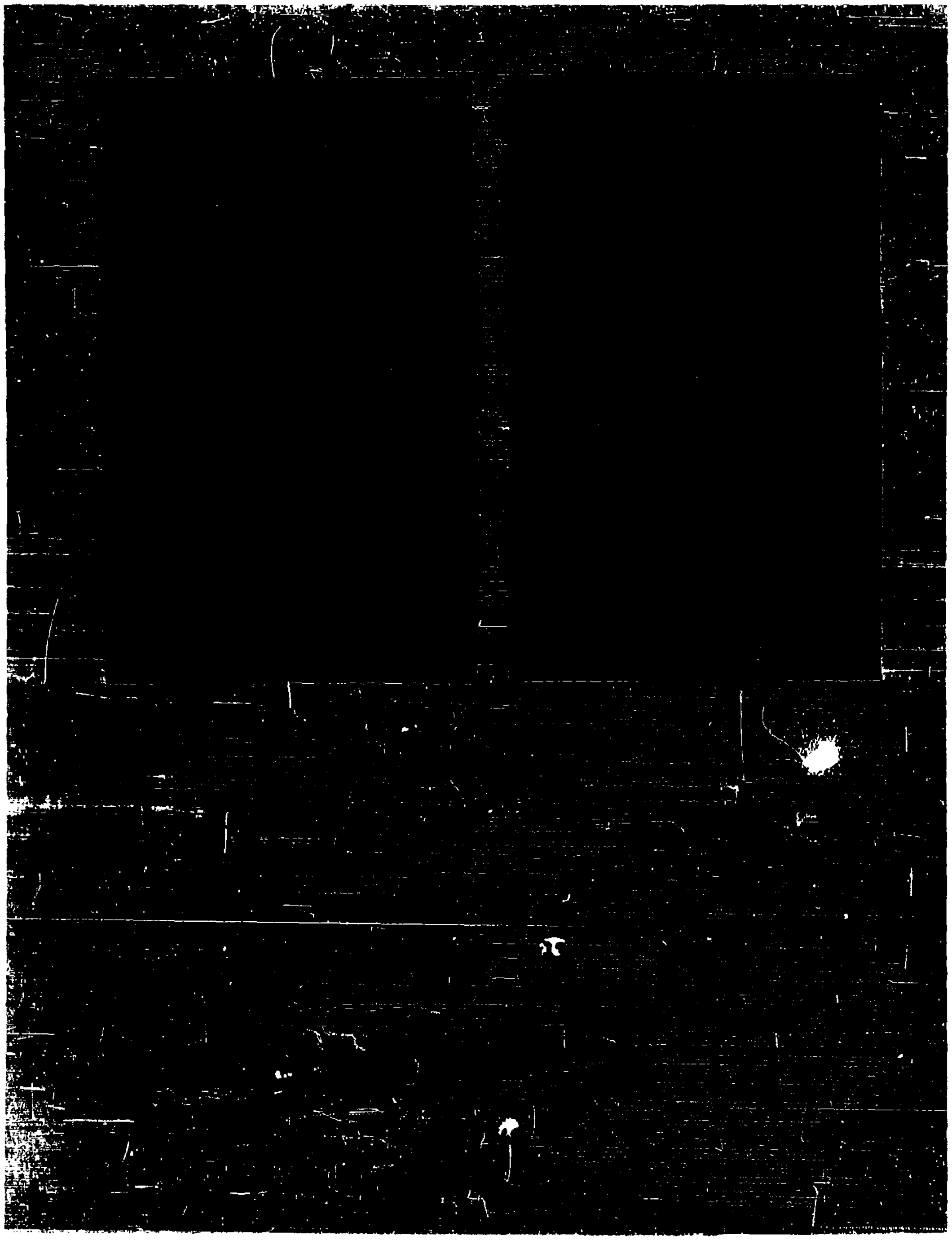
Specimen No. 3
Ultimate Strength 88,656 psi

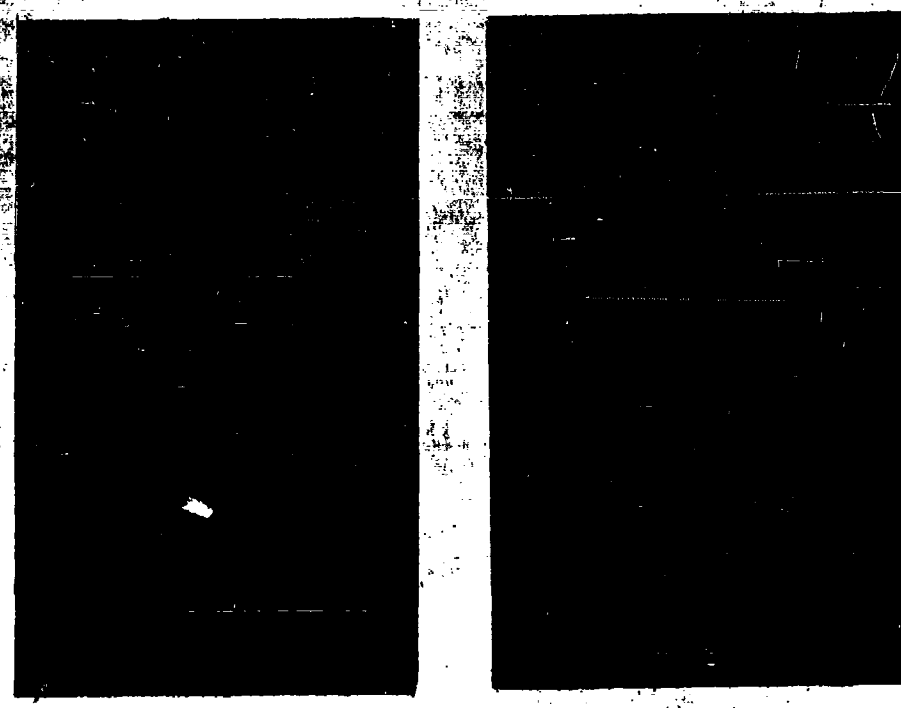
Test Temperature: Room
Base Material - Rene' 41
Braze Alloy (60Pd - 40Ni - 0.5Li)

Figure 11

APPEARANCE OF FAILED BRAZE SURFACES
AFTER BLOCK SHEAR TESTS 60Pd - 40Ni - 0.5Li ALLOY
(NEAR COMPLETE "WETTING")







Magnification 10X

Specimen No. 4
No Void Area
Ultimate Strength 49,245 psi

Specimen No. 5
5 Percent Void Area
Corrected Strength 45,194 psi

Test Temperature: Room
Base Material - Rene' 41
Braze Alloy PM 129 (35Au - 62Cu - 3Ni)

Figure 14.

APPEARANCE OF FAILED BRAZE SURFACES
AFTER BLOCK SHEAR TEST 35Au - 62Cu - 3Ni ALLOY

Magnification 10X

Specimen No. 11
10 Percent Void Area
Corrected Strength 51,447 psi

Specimen No. 12
5 Percent Void Area
Corrected Strength 63,957 psi

Test Temperature: Room
Base Material - Rene' 41
Braze Alloy PM 130 (82Au - 18Ni)

Figure 15

APPEARANCE OF FAILED BRAZE SURFACES
AFTER BLOCK SHEAR TEST 82Au - 18Ni ALLOY

Several of these parameters were relatively independent of the material being brazed. These independent parameters were the cleaning, atmosphere control, induction heating coil design, heating rate, and the power requirements. There was little difference in these parameters whether the material being brazed was Rene' 41, AM 350, or Type 347 stainless steel. These independent parameters will be discussed in the following paragraphs.

The other parameters were dependent upon the brazing alloy and/or the material being joined. These dependent parameters are the fitting or sleeve design, brazing alloy form, and the joint clearance or diametrical spacing. The dependent parameters are also discussed below.

4.3 INDEPENDENT BRAZING PARAMETERS

Cleaning

Cleaning procedures for each of the tubing and fitting materials to be used in this program had been previously established by the Contractor. These procedures were found to be entirely satisfactory for use in tube brazing.

The same procedure for pre-braze cleaning was used for all three of the tubing system materials, Rene' 41, Type 347 and AM 350 stainless steels. This cleaning procedure was as follows:

(1) Alkaline clean by immersion in Vitro-Klene (Turco Products), with Turco No. 4215 additive, for 15 to 20 minutes at a bath temperature of 170-200 F.

(2) Rinse in demineralized water.

(3) Pickle in inhibited nitric acid (7 to 9 percent HNO_3 plus 6 to 8 percent Turco 4104) at room temperature for 10 minutes.

(4) Rinse in demineralized water.

Atmosphere Control

All joints were brazed in dried argon gas. A pyrex glass tube, closed at each end by stainless steel fittings, was used as a plenum chamber to retain the argon gas around the joint and also to aid in positioning the tube and sleeve assembly within the induction coil. Typical assemblies set up for brazing are shown in Figures 16 and 17. Disassembled fittings, pyrex plenum chambers, and various sizes of induction coils are shown in Figures 17 and 18.

Dried argon gas was introduced into the plenum chamber through one of the end fittings and flowed between the metal tube and the pyrex tube, as indicated on Figure 19. Dried argon gas was also flowed through the inside of the metal tube. In this way all surfaces of the joint assembly to be brazed were in an argon atmosphere. Incoming gas flows were balanced so the pressure was approximately equal on the inside and outside of the tube joint assembly. If the gas flow pressures were not maintained equal, there was a tendency for the argon gas to pass through the molten brazing alloy, causing voids in the brazed joints or expelling the molten brazing alloy from the joint capillary.

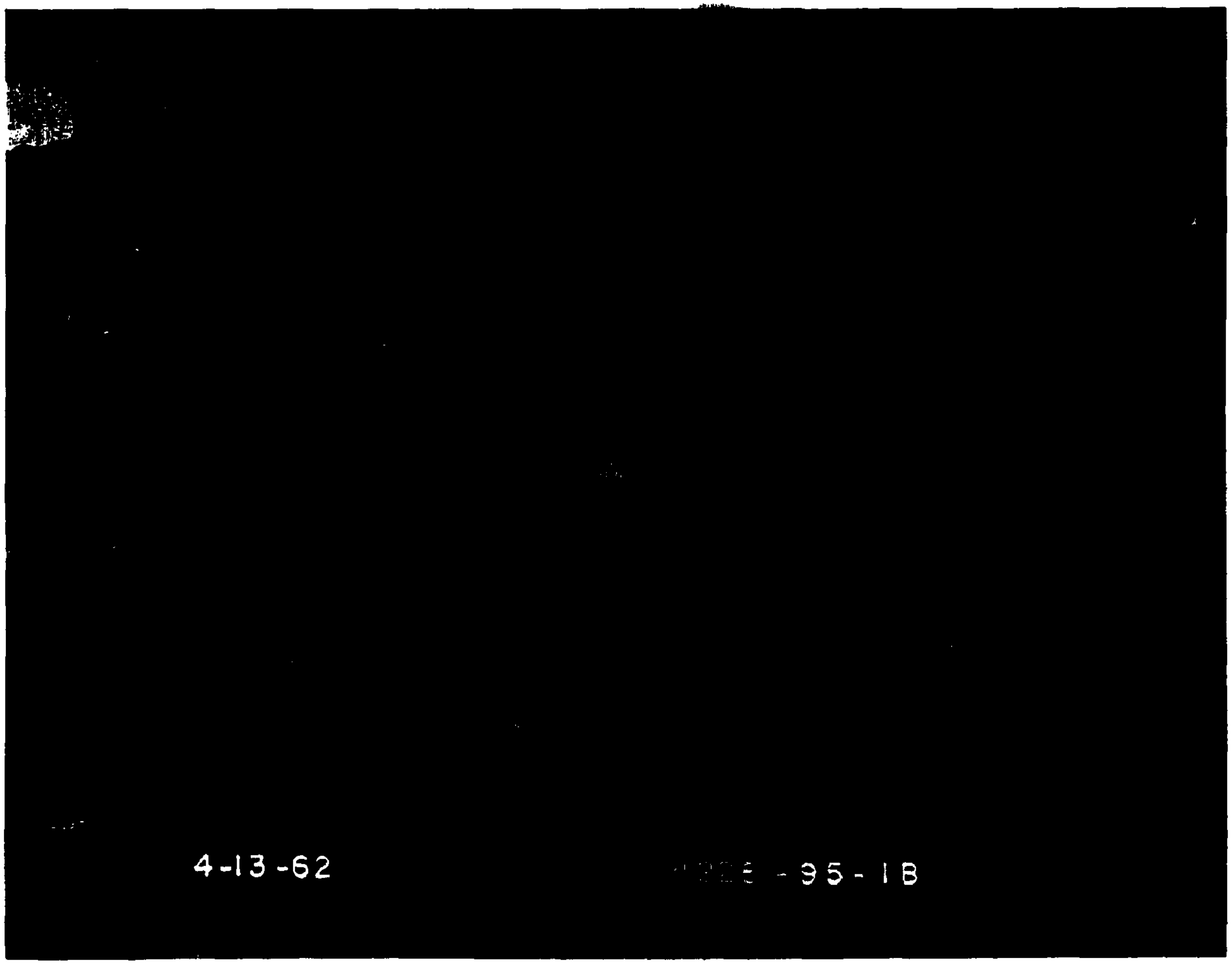


Figure 16. Induction Brazing Tooling Set-Up (Assembled)

Figure 17. Display of Induction Brazing Tooling and Brazed Joints

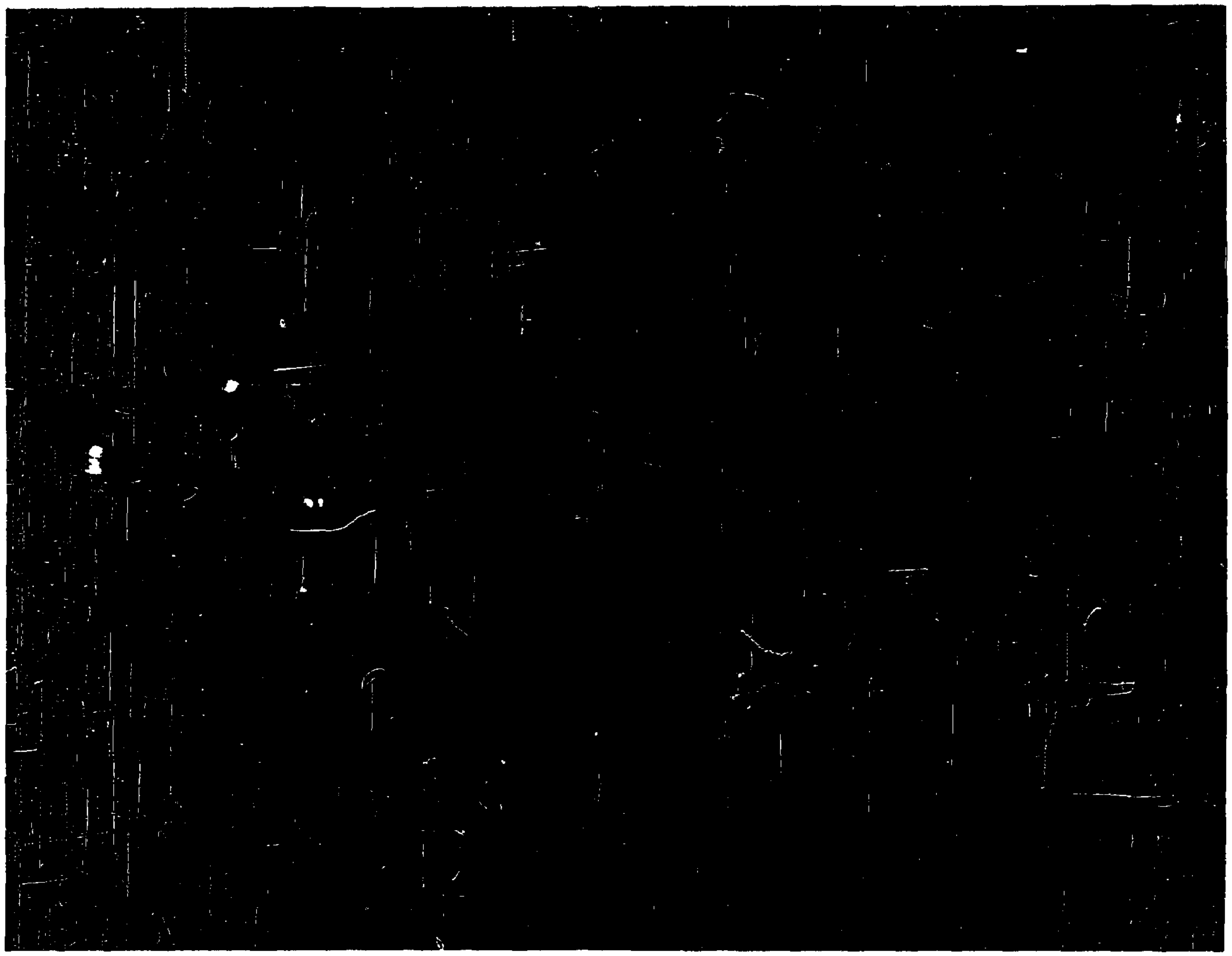


Figure 18. Induction Brazing Plenum Chamber and End Fittings (Disassembled)

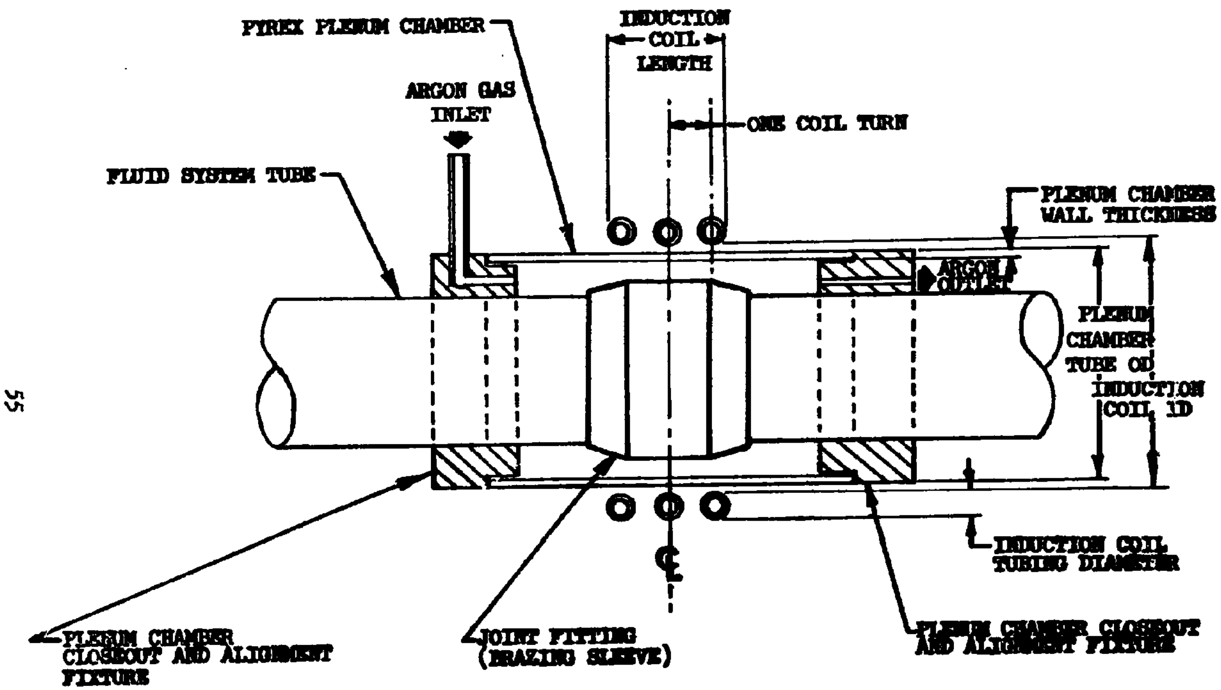


Figure 19. Schematic of Braze Tube Joining Tooling Set-Up.

A specially built drying train was used to ensure that the argon gas was dried to less than ten parts per million of moisture before the gas was passed through the brazing apparatus. In addition, low flow rates of the dried argon gas were used during brazing to further minimize the possibility of introducing traces of moisture with the argon. The argon gas flow rates were controlled to prevent air from entering the plenum chamber and contaminating the enclosed joint assembly during the brazing cycle, and particularly when the argon atmosphere in the plenum chamber contracted in volume during rapid cooling of the system after brazing.

Coil Design

Design of the induction heating coil for tube brazing includes consideration of four variables. These variables are:

(1) Coil length
(2) Coil diameter
(3) Number of turns in coil
(4) Size and shape of the tubing used to form the coil

The relationship of the above variables, the plenum chamber, and the joint assembly to be brazed, are shown in Figure 19. The length of the coil is determined by the length of the area to be heated, in the case of this program, the length of the fitting. Satisfactory joint brazing was achieved for the joints made in the Phase I part of this program when the coil length was equal to the fitting length. Variations of 1/16 to 1/8 inch in the coil length did not appear to have any detrimental effects on the brazing process or the quality of the joint. The coil length may be increased or decreased if more or less heat is required at the ends of the fitting in order to accomplish satisfactory brazing.

The inside diameter of the induction coil is normally made as small as possible consistent with the size of the plenum chamber. The spacing between the inside diameter of the induction coil and the outside of the work piece is called the "coupling" of the coil to the work. In general, the efficiency of induction heating is greatest when the coupling or space between the coil and the work is as close as is possible without causing the electric current to arc from the coil to the work piece. However, there are times when the coil diameter is increased in order to decrease the flux intensity and produce a more even heat input into the work. Dimensions of the pyrex plenum chamber tubes and the induction heating coils as used for several sizes of brazed tube joints during the Phase I part of this program are given in Table XII. The sizes given in this table are indicative only, inasmuch as they are dependent on the wall thickness or outside diameter of the particular fitting used to make the joint, and also the coil diameter will be varied according to the requirements established by the ferromagnetic characteristics of the tubing and fitting materials.

TABLE XII. DIMENSIONS OF TOOLING USED FOR INDUCTION BRAZING OF DIFFERENT SIZES OF TUBING.

DIAMETER OF TUBING TO BE BRAZED	PYREX PLENUM CHAMBER DIMENSIONS *		INDUCTION COIL INSIDE DIAMETER
	OUTSIDE DIAMETER	WALL THICKNESS	
1/8 in.	10 mm (0.394 in.)	1.0 mm (0.039 in.)	13/16 in.
1/4 in.	15 mm (0.590 in.)	1.2 mm (0.047 in.)	13/16 in.
1/2 in.	25 mm (0.985 in.)	1.5 mm (0.059 in.)	1-1/8 in.
3/4 in.	30 mm (1.181 in.)	2.0 mm. (0.079 in.)	1-1/4 in.
1 in.	38 mm (1.496 in.)	2.0 mm (0.079 in.)	1-5/8 in.
2 in.	75 mm (2.953 in.)	2.4 mm (0.095 in.)	2-1/8 in.
3 in.	120 mm (4.724 in.)	3.0 mm (0.118 in.)	4-7/8 in.

Notes: * Glass tubing for these plenum chambers was procured to millimeter size dimensional standards. Dimensions in inches are shown for information only.

The power output, or heating efficiency, of the induction heating system is determined in great measure by the match between the electrical characteristics of the induction generator, the power transmission cable and the coil. It is particularly important that the impedance of the transmission cable together with that of the coil-workpiece combination be properly matched to the impedance of the induction generator circuit. The impedance of the induction coil can be changed somewhat by increasing or decreasing the number of turns of copper tubing which make up the coil. The length of the area of the workpiece which is to be heated is a consideration in determining the number of turns of the coil, but the matching of the electrical characteristics of the circuit is by far the most important consideration. The coil length can be increased by spreading the turns farther apart, if necessary, without increasing the number of turns.

The number of coil turns required to satisfactorily braze a given tube joint and fitting combination will not be the same when different induction generators are used. This was demonstrated during the development of brazing parameters for 3/4 inch O. D. x 0.030 inch wall Rene' 41 tubing. A three-turn coil produced uniform heating of the joints on the 30 KW Ther-Monic Induction Heating Unit, but a four-turn coil was required to obtain uniform heating and good quality brazed joints when the 2-1/2 KW Lepel Induction Heating Unit was used.

The size, or diameter, of the tubing used to form the work coil as well as the tubing shape, whether round, square, or flattened, is selected to fit the joint design, tubing and fitting material, and the induction generator which is to be used. The work coil which was used to braze the joints in the 1/4 inch diameter AM 350 stainless steel tubing was made from 1/8 inch diameter round copper tube. Round copper tubing 3/16 inch in diameter was used for the work coils with which the joints in tubing 1/2 inch and larger in diameter were brazed.

All tube joint brazing during the Phase I development work was done using hand-wound, open, water-cooled copper tube coils. The tube joint to be brazed was contained inside the glass plenum chamber. This type of arrangement is shown in Figures 17 and 19. It is satisfactory for bench or "shop type" brazing at the work station on the induction heating unit, and it can also be used at the end of a coaxial power transmission cable for "in place" brazing at locations remote from the induction unit. The plenum chamber can be made in two pieces for ease of removal from the joint after brazing. The hand-wound copper coil is inexpensive and can be discarded after use.

Where many joints of the same size and materials are to be brazed, the work coil can be made as a reusable split-type configuration, such as is shown in Figure 20. This is a production-type tool using an air cooled coil. It is designed for ease of use in an area of limited accessibility at a distance from the induction generator. This tool is provided with semiautomatic controls and does not require a high level of skill in the using personnel. Such a unit is satisfactory for precision machined fittings where the wall thickness and fitting diameters are held to close tolerances, and where the nature of the materials and the size of the joint do not require particularly large amounts of heat or long heating times. Should the use of "snap-on" or split-type tools for brazing of rocket fluid system tubing joints appear desirable, information on the design of this type of tooling will be prepared in Phase III.

Power Requirements and Heating Rate

Three induction heating units were available and were used in the Phase I part of the program. They are a 30 Kw, 250 Kc Ther-Monic unit; a 2-1/2 Kw, 450 Kc Lepel unit; and a 1-1/2 Kw, 450 Kc Lepel unit. The 30 Kw Ther-Monic unit was used to braze the large and intermediate size tube joints, and is expected to be required for all tubing joints two inches in diameter and larger. The 2-1/2 Kw Lepel unit and the 30 Kw Ther-Monic unit were both used for brazing the 1/2 inch and 3/4 inch diameter tube joints. The 1-1/2 Kw Lepel unit was used for brazing the small joints, such as the 1/8 inch and 1/4 inch diameter Type 321 and AM 350 stainless steel tube joints. All three of the induction heating units were found to be satisfactory heating sources for the tube joints brazed.

The power settings of the induction machines were initially kept sufficiently low to insure uniform heating of the tube fitting assembly during brazing. Slow heating rates were used during the development work in Phase I so that more time was available to observe the wetting and flow action of the brazing alloys. Heating times for all joints was between one and two minutes. The heating times used for brazing AM 350 tube joints in normal production operations frequently are of shorter duration, of the order of 20 to 45 seconds. Shorter heating times on the order of the production brazing cycles will be used where applicable in the manufacture of the Phase II qualification test specimens.

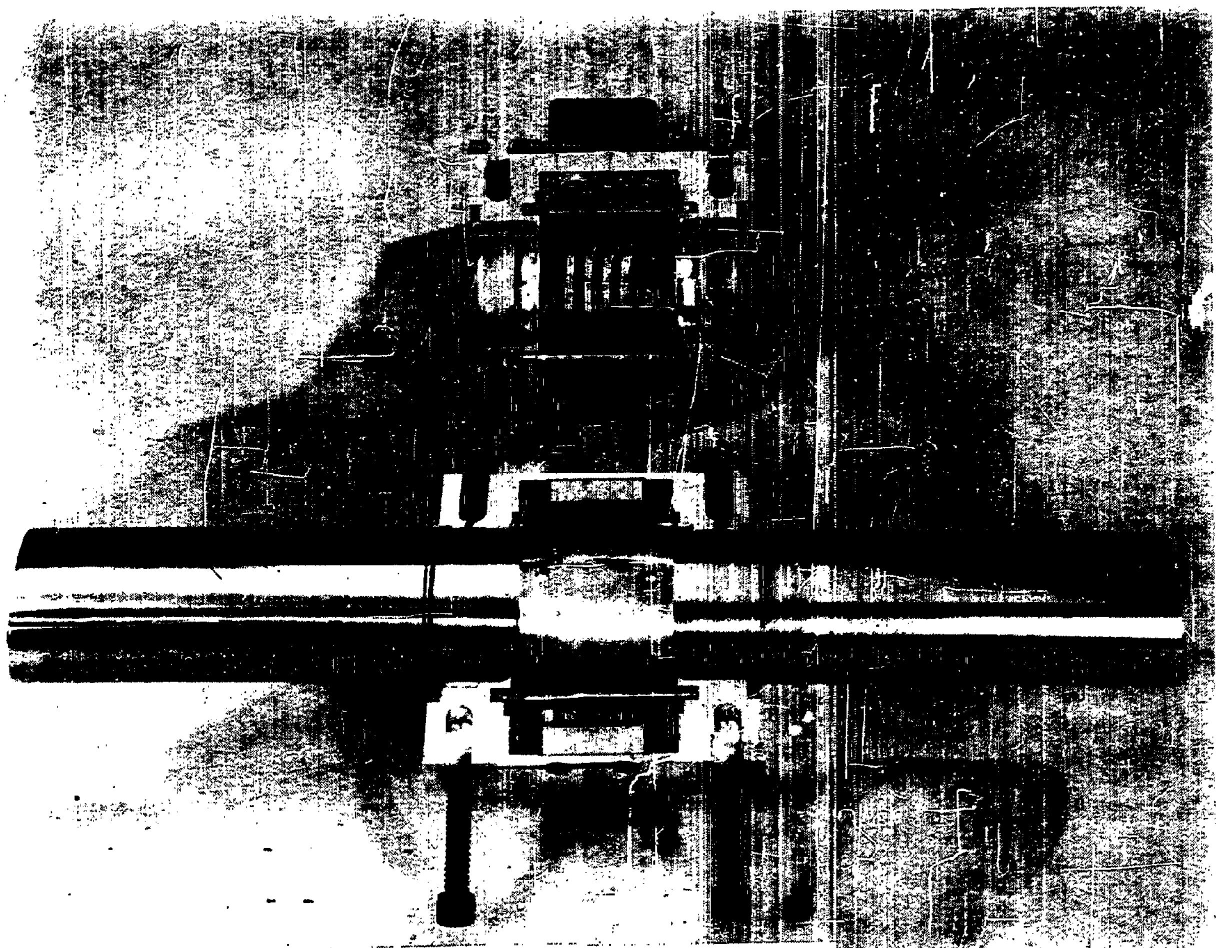


Figure 20. Split-Type Reusable Coil Induction Brazing Tool

4.4 DEPENDENT BRAZING PARAMETERS

Certain brazing parameters were previously classified as being dependent upon the brazing alloy and/or the material being joined. These were the fitting or sleeve design, the brazing alloy form, the joint clearance or diametrical spacing, and also the brazing alloy placement. The general requirements for fitting or sleeve design were discussed in Section 3, Structural Analysis. The other dependent parameters are discussed in the following paragraphs under each type of tubing material, and tube sizing procedures are described.

Rene' 41

The form in which each brazing alloy was used was governed first by availability and secondly by ease of handling or application. Premabraze 130 alloy was used as a preformed ring, and was preplaced within the grooved fitting or sleeve. Premabraze 128 alloy is not available as a preformed ring. This alloy was used in the form of a wire loop placed between the two tube ends inside the fitting. The 60Pd-40Ni-0.3Li alloy was available only in the form of thin foil. This alloy was pre-wrapped around the outside of the tube ends, and then a straight-through (ungrooved) fitting was pressed over the braze alloy wrapped tube ends.

The joint clearance for the Rene' 41 joints, or the diametrical gap between the tube O.D. and the fitting I.D. was 0.003 inch for the Premabraze alloys 128 and 130; and was 0.003 to 0.004 inch for the 60Pd-40Ni-0.3Li alloy, depending on the thickness of the brazing alloy foil.

Type 321 and 347 Stainless Steel

Type 321 stainless steel was used to develop the brazing parameters for the system in which Type 347 stainless steel tubing will be used. The two steels are very similar in their brazing properties. Premabraze alloy 130 again was used as a wire preform in conjunction with a grooved fitting. The joint clearance was 0.003 inch. BT + lithium brazing alloy was also used as a preformed wire ring preplaced inside a grooved fitting. Because of the fluidity of the BT + lithium alloy, a slightly closer joint clearance of 0.0025 inch was used.

AM 350 Stainless Steel

BT + lithium was the only brazing alloy used with the AM 350 stainless steel tubing. This alloy was used in the same wire preformed ring and with the same design of fitting as with the Type 321 tubing described in the preceding paragraph.

Tube Sizing

Tube sizing generally is necessary in order to produce high quality production-type brazed joints. Sizing of tubing may be required to correct for the effects of the outside diameter and ovality tolerances of commercial tubing, and also for out-of-tolerance conditions which may result from any tube forming operations.

Tube sizing can be accomplished satisfactorily in the hydraulic punch press; however, this method cannot be used to size tube in place on systems during final assembly and in field repair maintenance. To accomplish tube sizing in all stages of assembly and field maintenance repair, a portable, high energy tube sizing tool may be used. A tool of this type, as shown in Figure 21, has been developed by the Contractor and is being used in the assembly of tubing systems for the XB-70. This high energy tube sizing tool can be used in the field under normal safety precautions. High energy to size the tube is obtained by the expansion of gases of a .22 caliber charge. The tool has split dies to correct tube OD and wall thickness, and when used sizes the tubing to 0.010 $^{+.003}_{-.000}$ inches above the nominal OD. This sizing tool can be used on tube diameters up to approximately two inches.

Tube sizing operations were not performed during the brazing investigation of the Phase I part of this program. Instead, the experimental sleeve fittings were selectively fitted to the tubing.

4.5 EVALUATION OF BRAZED JOINTS

Rene' 41 Tube Joints

Of the three brazing alloys selected for evaluation with Rene' 41 tubing, only Premabraze alloys 128 and 130 produced satisfactory brazed tube joints. Both of these brazing alloys produced joints that were 90 to 95 percent void free. On the basis of the shear strength data shown in Figures 3 and 4, both brazing alloys are expected to produce joints that will pass the burst test requirements at 1500 F. Premabraze alloy 128 is expected to develop a slightly higher shear strength at 1500 F than is Premabraze alloy 130. However, Premabraze alloy 130 is readily available as a preform ring while Premabraze alloy 128 is not. Preform rings of brazing alloy have the advantage of being easier to use and produce more reproducible quality joints. Therefore, because of its availability as a preform ring, Premabraze alloy 130 has been selected as the recommended alloy for brazing Rene' 41 tube joints. Should it prove possible to procure Premabraze alloy 128 as preformed rings at some later date, then this alloy would be recommended because of the higher shear strength which it is expected to develop at 1500 F.

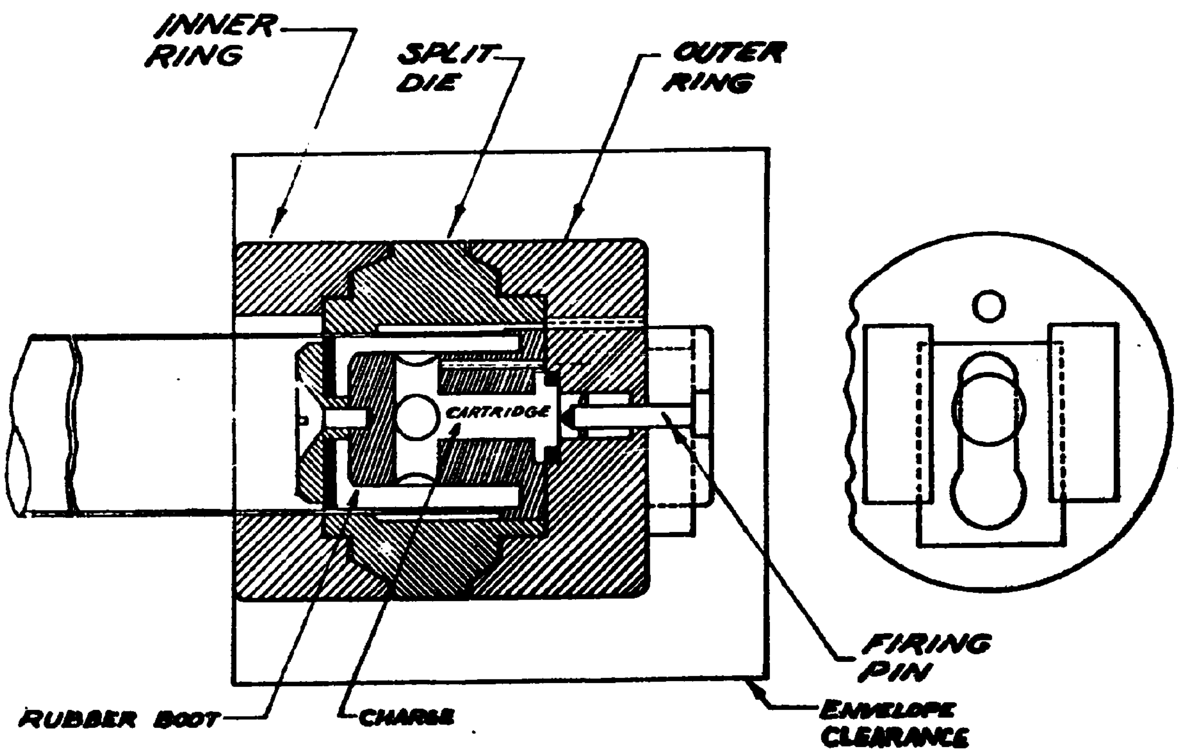


Figure 21. Portable High-Energy Tube Sizing Tool.

At the start of the brazing parameter development work, difficulty was encountered in obtaining satisfactory flow of the gold-base brazing alloys along the Rene' 41 tube joint capillary. This difficulty is believed to result from the presence in Rene' 41 alloy of the elements aluminum and titanium. These elements are thought to form oxides on the tube and fitting surfaces, the oxides inhibit wetting and flow of the brazing alloy. This problem was overcome by nickel plating the Rene' 41 alloy tube and fitting surfaces to be brazed. The gold-base brazing alloys were able to wet the nickel plating and flow easily through the joint capillary. Excellent joints, such as the one shown in Figure 22, were obtained by this technique.

The 60Pd-40Ni-0.3Li brazing alloy had shown great promise during the initial evaluation work with the wetting and block shear specimens. Excellent block shear strength was attained at all temperatures from sub-zero to 1500 F. Then, difficulties were encountered during the preliminary attempts to braze Rene' 41 tube joints. The high melting temperature of this alloy (2100 F) required a brazing temperature of 2150 F. Currently, the 60Pd-40Ni-0.3Li alloy is available commercially only in the powder form. The alloy used for the tests under this program was prepared in the NAA Laboratory by vacuum induction melting, and then rolled to 0.003 inch thick foil. The first melt of this alloy was used for the preliminary tests and produced the excellent results. Two successive attempts to reproduce this alloy were unsuccessful. For reasons which were not readily apparent, both lots of alloy had melting points above 2150 F. When these lots of alloy were used to braze tube joints, brazing temperatures of 2200 F or higher were required. Under these conditions incipient melting and deformation of the tube joint occurred.

Inasmuch as the shear strength of the gold-base alloys were determined to be adequate for the Rene' 41 tube system requirements under this program, the 60Pd-40Ni-0.3Li alloy was dropped as a candidate braze alloy for this program. However, it is believed that development of this alloy should be pursued further. The problems encountered are thought to have been caused by variations in the lithium content, which has a great effect on the melting point of the alloy.

The 60Pd-40Ni-0.3Li alloy lot first made had good wetting and flow characteristics with Rene'41. It was not necessary to nickel plate the Rene' 41 surfaces in order to obtain satisfactory wetting, as was the case with the gold-base alloys. The strength characteristics of the block shear specimens at 1500 F were excellent. This alloy should prove satisfactory for use with other high-strength high-temperature tubing materials, such as Haynes alloy HS-25. Further development of this brazing alloys is, therefore, recommended under a separate development program.

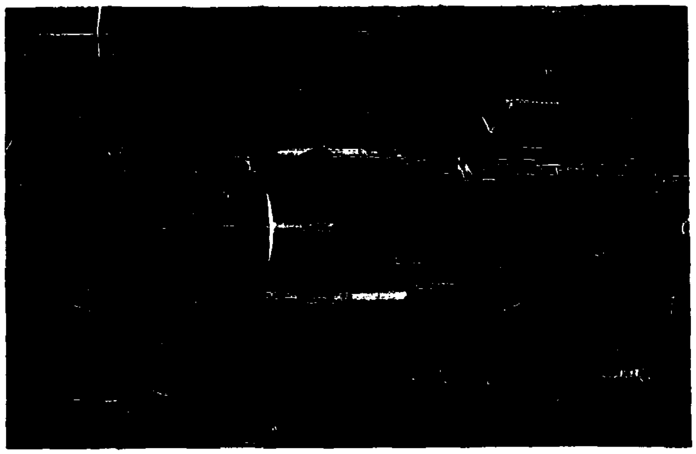


Figure 22

TYPICAL BRAZED TUBE JOINT PRODUCED WITH [illegible] 41.
SURFACES TO BE BRAZED WERE NICKEL PLATED.

Type 321 Stainless Steel Tube Joints

The most satisfactory brazed joints with Type 321 stainless steel tubing were made with the BT + lithium brazing alloy. Joints were produced with this alloy which were 95 percent void free.

Early joints brazed with the BT + lithium alloy and Type 321 stainless steel tubing had many voids. These voids were determined to have been caused by mill markings on the tubing which the chemical cleaning operation had not completely removed. This condition was corrected by vapor honing the tube surface prior to the regular cleaning operation.

Premabraze alloys 128 and 130 produced brazed Type 321 stainless steel tube joints which were approximately 80 percent void free. The quality of the joints brazed with these gold-based alloys would probably have been further improved if the nickel plating technique discussed above had been used in the same manner as with the Rene' 41 joints. However, since the BT + lithium alloy produced very satisfactory quality brazed joints in the Type 321 stainless steel, further work on development of brazing parameters for the gold-based alloys with the Type 321 stainless steel tubing was discontinued.

AM 350 Stainless Steel Tube Joints

The BT + lithium braze alloy wetted and flowed very well in the AM 350 stainless steel tube joints. The experimental AM 350 tube joints made with this braze alloy were approximately 70 percent void free. This is well below the quality level which is normally obtained in production brazing of AM 350 tube joints with these materials. Examination of the test joints showed that the joint clearance had increased during the brazing operation. The dimensional tolerances of the joint have been established with the expectation that the sleeve would contract slightly during the braze cycle. It is believed that the AM 355 stainless steel sleeves used for the test joints were not in the required heat treat condition and that as a result the sleeve underwent dimensional growth rather than the expected shrinkage. This problem is not expected to occur again since a close inspection will be made of tubing and fitting materials intended for use in this program. As shown in Figure 9, BT + lithium brazed joints are expected to have a block shear strength of 22,000 psi at room temperature, 20,000 psi at 200 F, and 12,000 psi at 600 F, Reference (18).

4.6 JOINT REBRAZING FEASIBILITY STUDY

A feasibility study has been initiated on the problems associated with debrazing and rebrazing of joints made with the materials used in this program. The preliminary rebrazing study was conducted with a simple butt joint specimen made from Rene' 41 rectangular bar. The brazing alloys investigated with Premabraze 130 and 60Pd-40Ni-0.3Li alloy. The brazing, debrazing, and rebrazing operations were performed with the apparatus shown in Figure 23.

The Rene' 41 butt joint made with Premabraze 130 alloy was debrazed and rebrazed a total of five times. These operations were conducted at temperatures both above and also somewhat below the nominal 1742 F melting temperature of this brazing alloy. It was possible to pull the joint apart at temperatures of the order of 1600 F to 1650 F, and then cause the alloy to rebond at temperatures of 1650 F to 1700 F. This was done in an argon atmosphere. The debonding and rebonding below the melting temperature of the brazing alloy can be accomplished because of the particular nature of gold alloys as regards their known malleability and dry welding or pressure bonding characteristics, Reference (20). The joints were examined after each braze operation and were found to be of sound quality with no apparent voids or discontinuities.

The joints made with the 60Pd-40Ni-0.3Li alloy were brazed and debrazed twice and then rebrazed a third time. Examination of this joint showed a poor quality braze after the third braze operation. It appeared that the lithium in this brazing alloy had dissipated during the first two brazing and debrazing operations. Since the lithium in this alloy served as a volatile flux and also improved wettability and flow characteristics, when it was gone the brazing alloy was no longer capable of proper wetting and flow to reform a sound joint. In this connection, it can be expected that the silver-base brazing alloys which contain lithium as a fluxing agent will react in a similar manner. That is, they will be capable of only a very limited number of debrazing and rebrazing operations because of lithium volatilization and depletion from the alloy.

An attempt was made to debraze and rebraze the nickel plated and brazed Rene' 41 tube joint shown in Figure 22. This joint was made with Premabraze 130 brazing alloy. The joint was successfully debrazed in an argon atmosphere. Examination of the debrazed joint showed good adhesion of the brazing alloy to the base metal, and full flow and wetting of the joint capillary surfaces. The rebrazing operation was not successful. During attempts to prepare the joint for rebrazing some of the brazing alloy was inadvertently removed from the joint surfaces. Then, during the rebrazing operation when the tube end was moved into the fitting at brazing temperature, air leaked into the plenum chamber through a defective end seal. This contaminated the argon atmosphere and caused the formation of oxide on the Rene' 41 surfaces and within the joint. Additional debraze-rebraze studies will be conducted to determine whether this procedure can be successfully used with brazed tube joints.

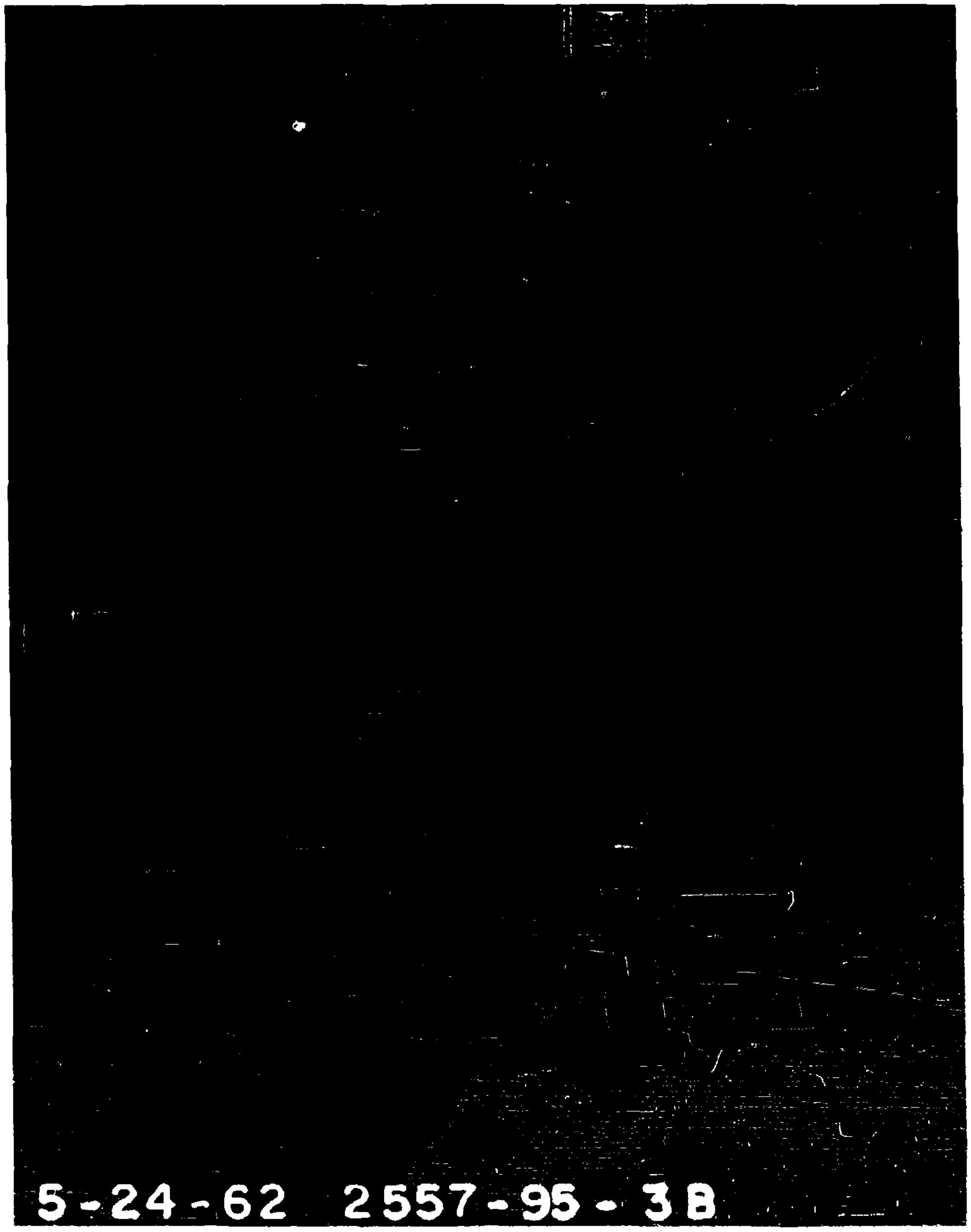


Figure 23. Apparatus for Rebrazing Feasibility Preliminary Tests.

5. TUBE WELDING

5.0 GENERAL

The use of fusion welding as a means of joining tubing for rocket fluid systems has inherent advantages over many other methods of assembly. Welded connections have a minimum weight addition at the joint, they have good strength at elevated temperatures, good fatigue properties because of the minimal change in section at the joint, and they require small accessibility space. Another very favorable asset of the welded joint is that usually only one material is involved. The problems of corrosion and inter-reactions between dissimilar materials are minimized. This is an extremely important consideration in the development of joint systems for compatibility with exotic fluids having high degrees of chemical activity.

5.1 WELDING TOOLS

Two tube welding units were used in the Phase I part of this program. One unit was an existing tool which the Laboratory had been using for other programs, and was suitable for joining small diameter tubing sizes up to a maximum of one-inch diameter. The second tube welding unit was designed, built, and has been checked out satisfactorily. This second unit was designed for joining larger size tubing. It has been used to weld tubing as large as three inches in diameter and as small as 3/4 inch in diameter. The first welding unit set up for welding 1/8 inch diameter tubing is shown in Figure 24. The second welding unit is shown in Figure 25.

In general, these tools are operated by a Boston ring gear driven by a variable speed motor through a flexible cable and a pinion gear, as shown in Figure 26. A tungsten electrode is mounted in the ring gear and travels around the circumference of the tube as the gear rotates. The tube to be welded is located in the tool by transite inserts which are machined to fit the outer diameter of the tube, as shown in Figure 27. In this manner, any tube which has a diameter of three inches or less can be accommodated in the tool by machining an appropriate set of transite inserts.

A Vickers 200 ampere, direct current, rectifier type power supply was employed for all welding tests. The controls for weld power, drive motor speed, and shielding gas flow were all mounted in a portable control box for convenient remote "in place" welding usage. This control box is shown in Figures 27 and 28, the latter picture showing a remote welding setup.

5.2 WELDING TYPE 321 STAINLESS STEEL TUBING

Preliminary weld parameters were developed using type 321 stainless steel tubing. This material is similar to the type 347 stainless steel tubing which is to be used for the qualification test specimens in Phase II of this program. The type 321 material was available in laboratory stock and has been used pending procurement of the type 347 stainless steel

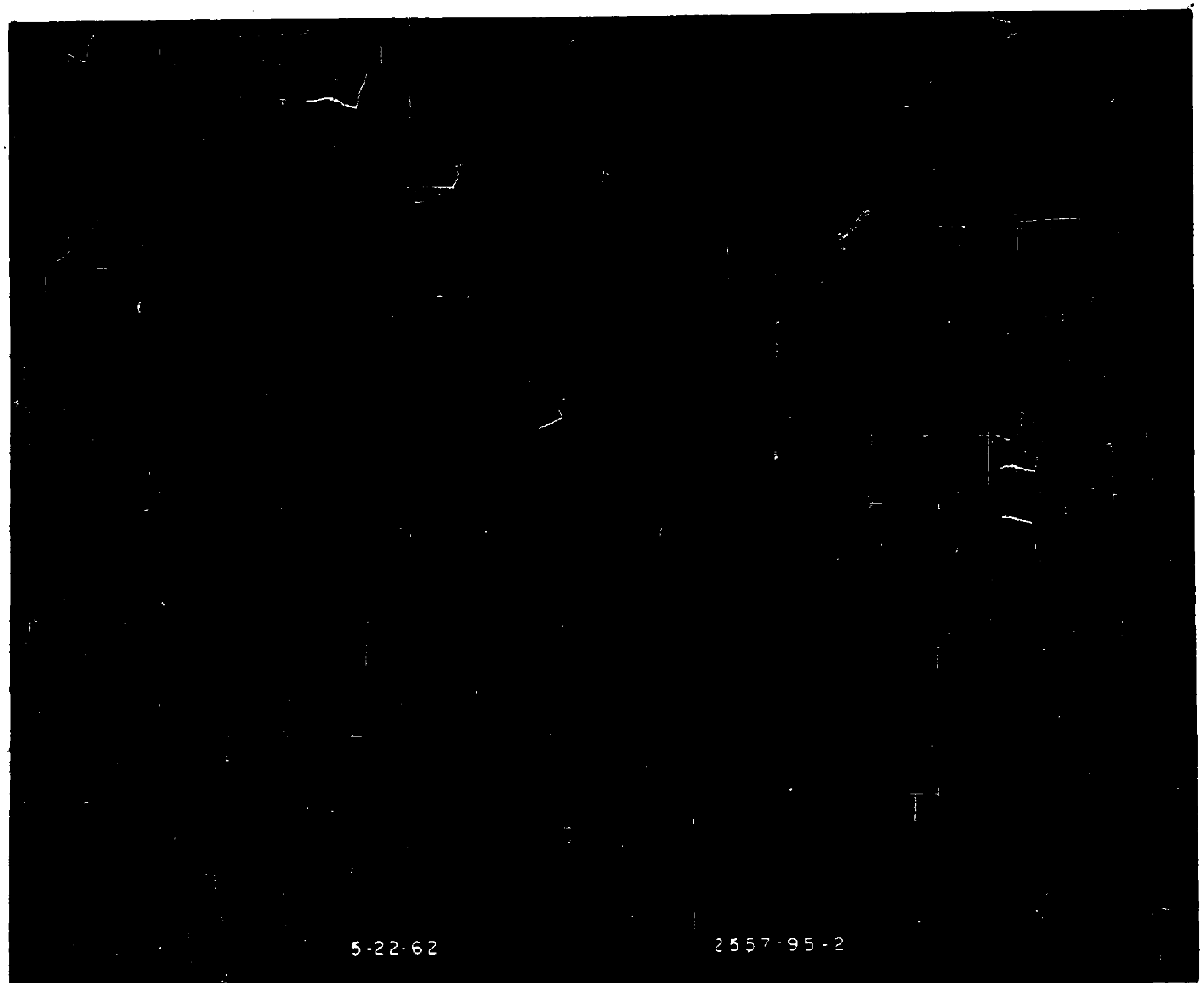


Figure 24. Tube Welding Unit for Joining Tubing Sizes from 1/8 Inch to One Inch in Diameter.

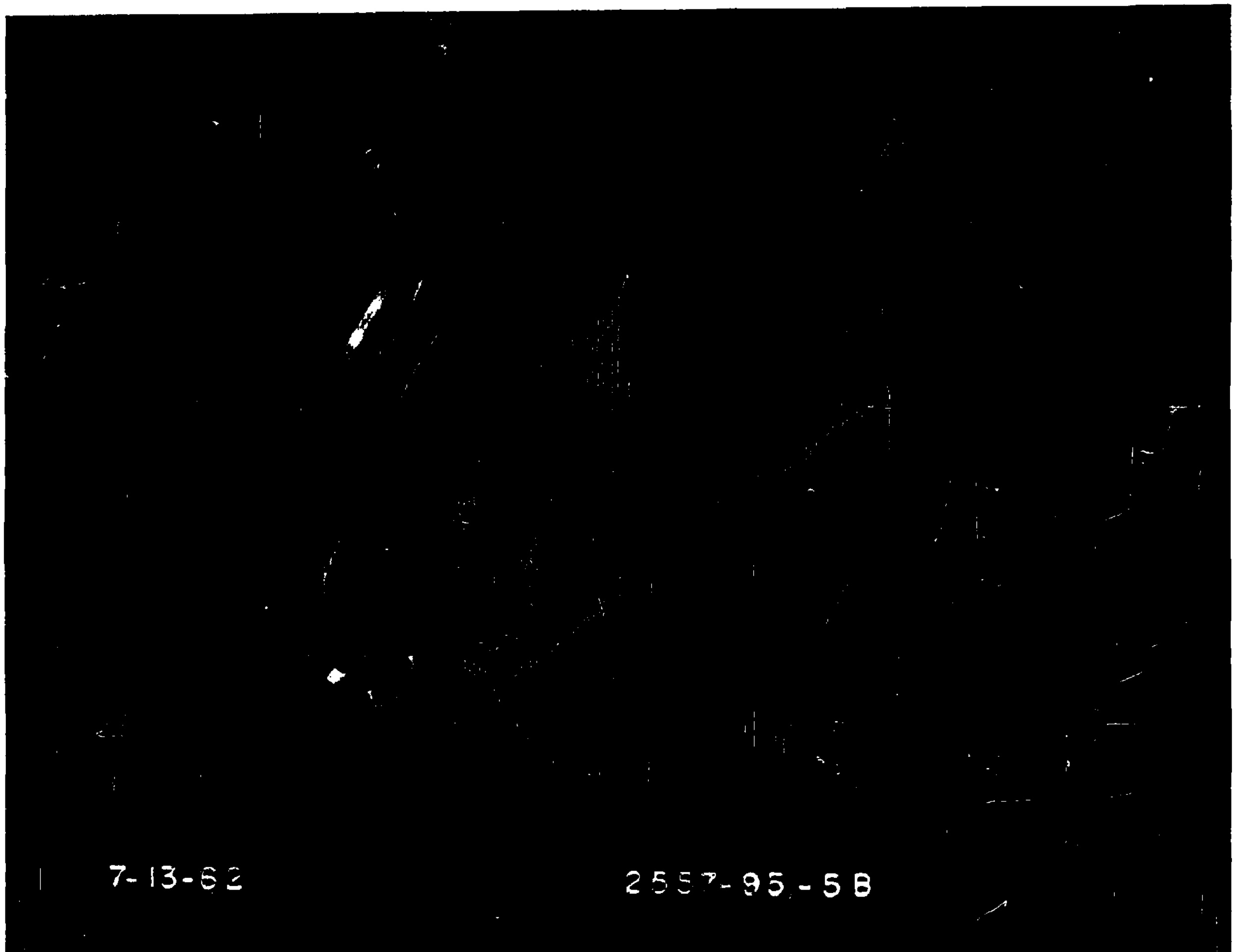


Figure 25. Tube Welding Unit for Joining Tubing Sizes up to Three Inch Maximum Diameter. (Partially Disassembled View Shows Tool with Electrode in Overhead Welding Position and Transite Inserts for Positioning Tube and Closing Ends of Plenum Chamber.)

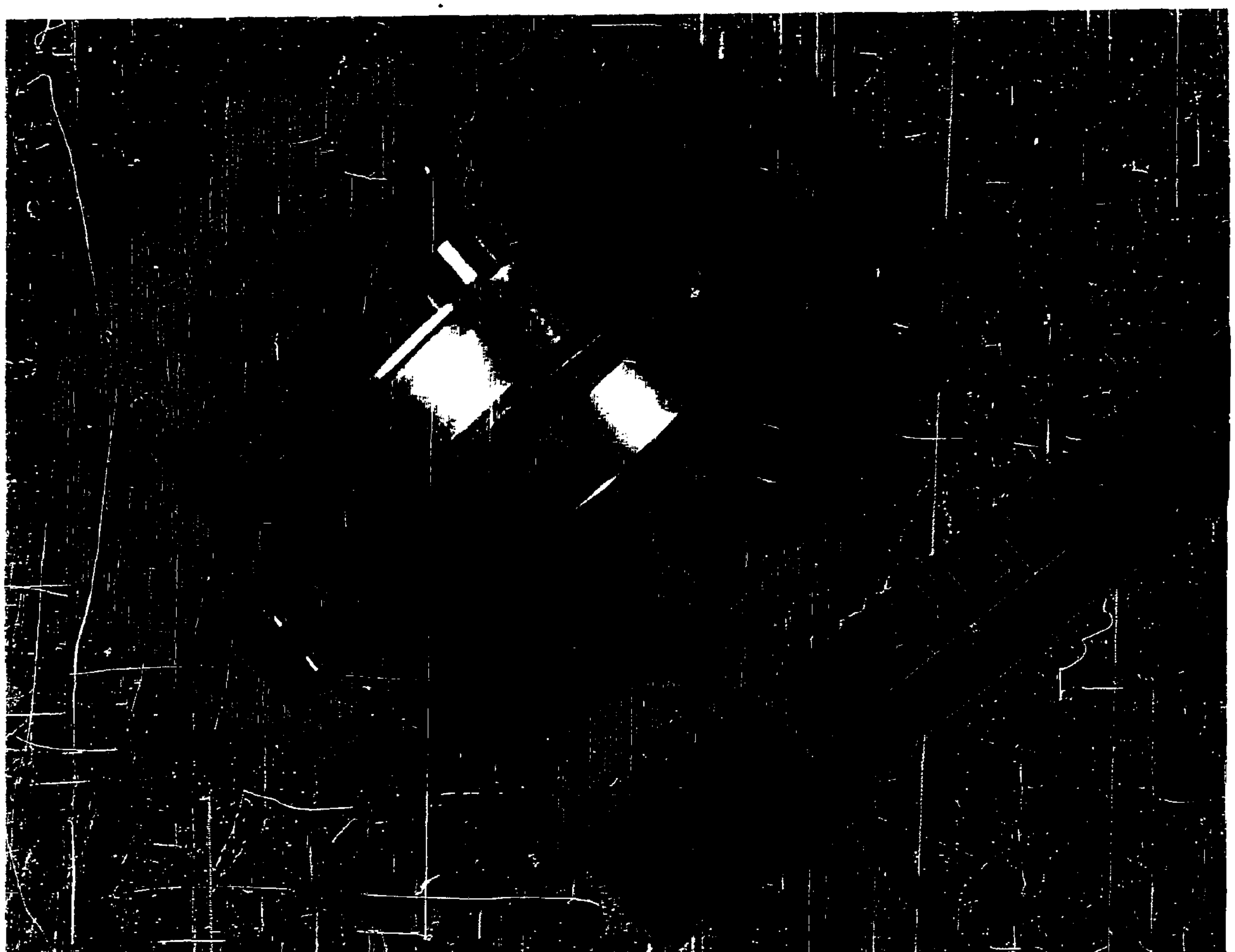


Figure 26. Tube Welding Unit for Joining Tubing Sizes Up to Three Inch Maximum Diameter. (Transite Inserts Removed to Show Electrode Drive Mechanism)

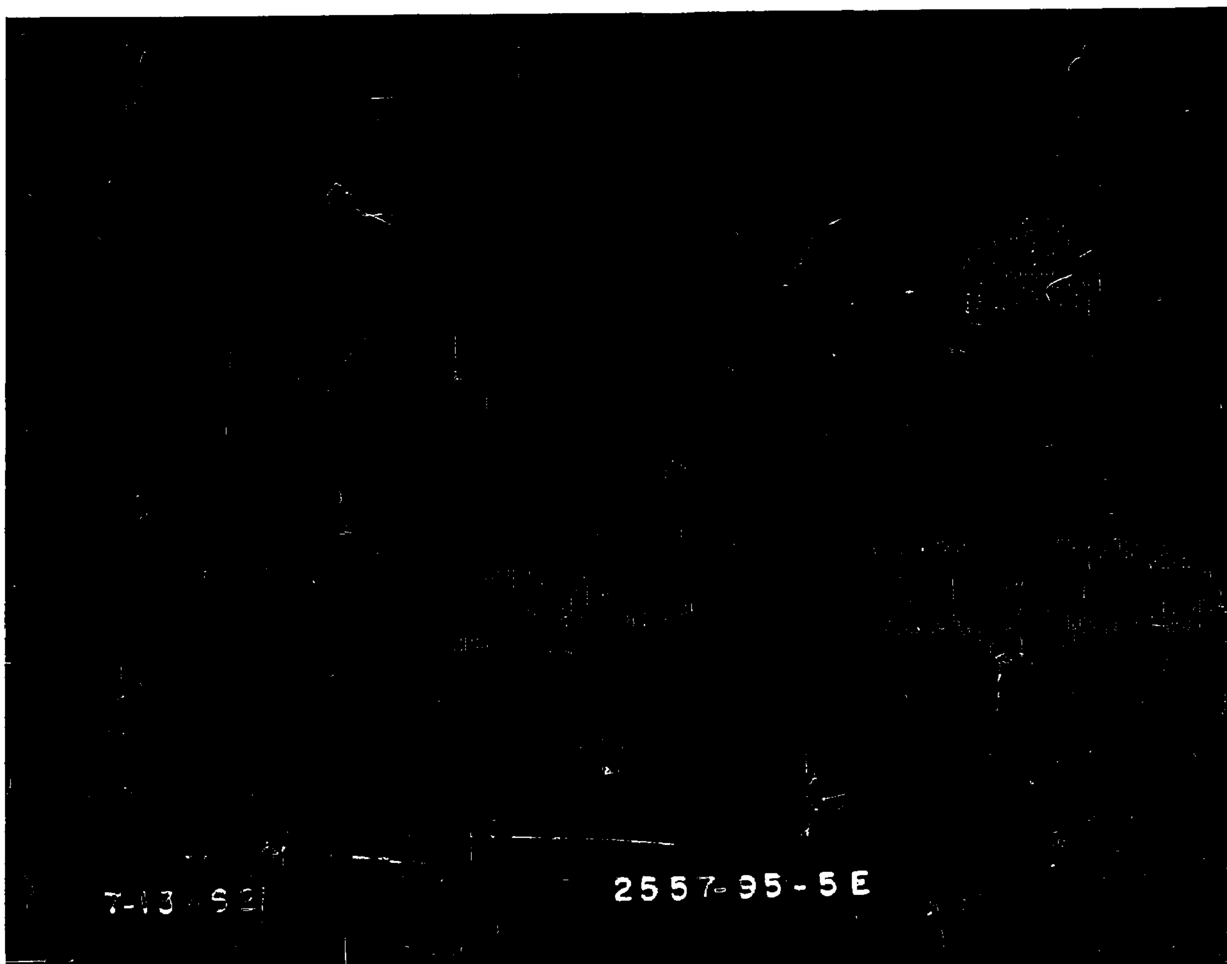


Figure 27. Tube Welding Unit for Joining Tubing Sizes up to Three Inch Maximum Diameter. (Partially Disassembled View Showing Welding Tool, Drive Motor, and Remote Control Box.)

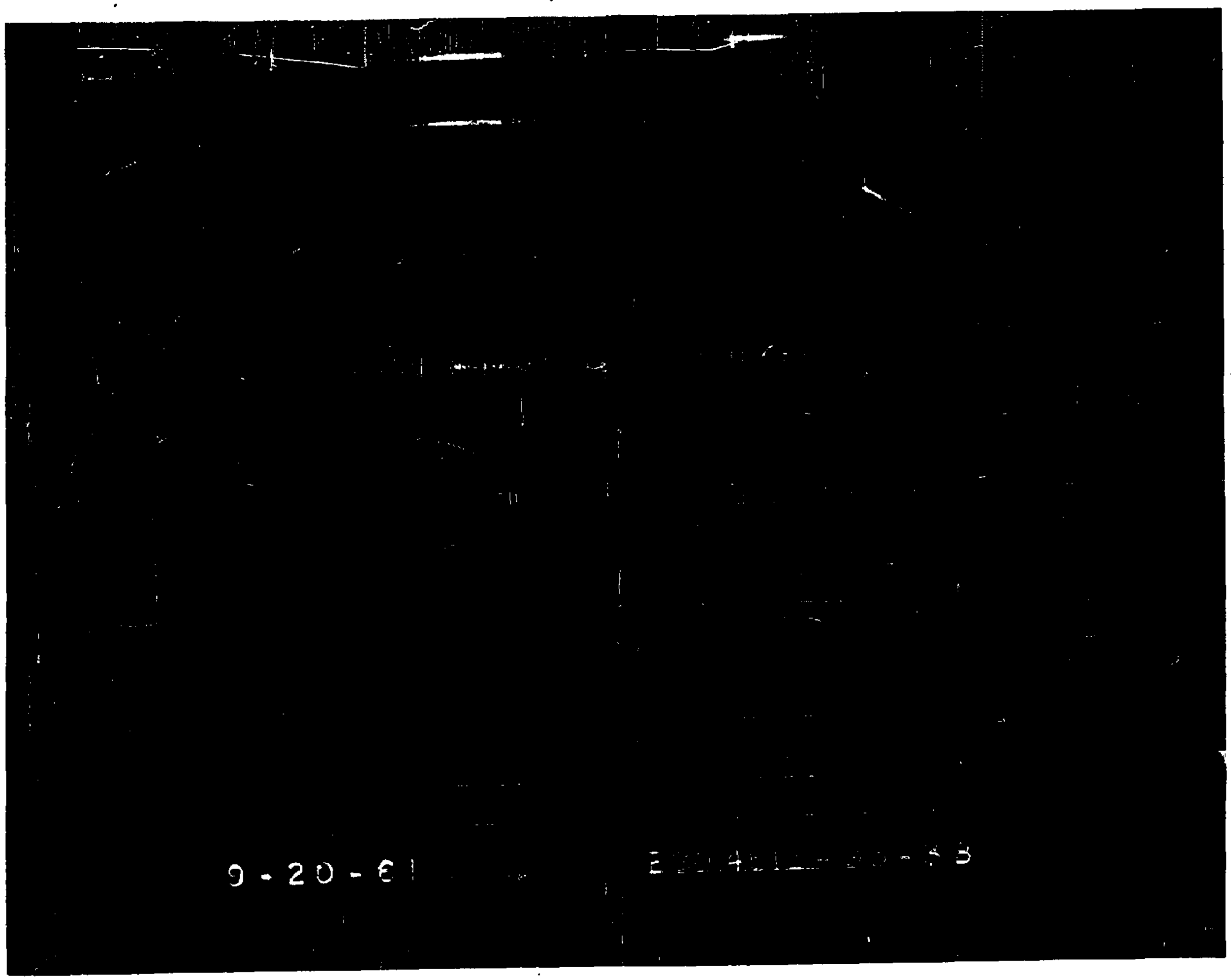


Figure 28. Tube Welding Unit Set Up for Joining One Inch Diameter Tubing in Area of Limited Access.

tubing. The major difference between the two materials is in minor additions of stabilizing agents to prevent chromium depletion during welding. It is not anticipated that any new major differences or problems will be encountered in joining type 347 stainless steel tubing. During this part of the Phase I work, the welding characteristics of 1/8, 1, and 3 inch diameter type 321 stainless steel tubing were investigated.

All of the welds made in the type 321 stainless steel tubing were stainless steel wire brushed and cleaned with acetone prior to welding. This cleaning procedure was adequate to produce a clean weld deposit.

Welding 1/8 Inch Diameter Tubing

The 1/8 inch diameter tubing was welded using the tool and set up shown in Figure 24. This tool had been designed and built by the NAA Laboratory under a previous program to weld tubing up to a maximum diameter of one inch in size. This tool, being designed for small diameter tube joining, is easier to use on the 1/8 inch diameter tubing than is the larger welding tool which was built for this program.

Some difficulty was encountered in welding the 1/8 O.D. x .012 inch wall thickness tubing due to an inability to "fire" the smaller welding tool at the low current levels which had to be used. This problem was aggravated by the fact that the smaller welding tool did not have a built-in voltage control which would allow touch start. Eventually, by coating the electrode tip with graphite, it was possible to "fire" consistently in the 2 to 3 ampere range of welding current settings.

Weld schedules were developed for the thin wall tubing. In these schedules the drive motor was started first, then the welding current was manually increased to the level for welding, about 10 amperes. To prevent crater cracking, after the weld was completed around the tube the welding current level was manually decreased while the travel speed of the welding electrode was increased.

Argon inert gas shielding was used on the torch side and helium gas shielding was used on the back-up side of the weld. Filler metal was added to the weld by melting down the sleeve fitting. This fitting, which was machined from type 321 stainless steel rod, also served to align the tube ends for the welding operation. The resulting welds were examined visually. Reproducible welds of good quality were made using this method in both the horizontal and vertical positions.

Welding One Inch Diameter Tubing

One inch diameter, .035 inch wall thickness, type 321 stainless steel tubing was welded using the tool designed and constructed for this program. No difficulties were encountered with operation of the tool in regard to tube alignment, shielding gas coverage or mechanical operation of the tool.

Welding schedules which were developed for the one inch tubing included the manual downsloping (reduction) of the weld current and an increase of the travel speed after one revolution to eliminate crater cracking. Upsloping (increase) of the magnitude of the weld current was not required. Filler metal addition and tube end alignment were accomplished by use of a sleeve fitting which was made by slightly expanding the diameter of a section of the one inch diameter tubing. Again, argon shielding gas was used on the torch side and helium gas shielding on the backup side of the weld. Radiographic and metallographic inspection showed that satisfactory welds were made in both the vertical and the horizontal positions.

After developing the final weld parameters, reproducible "blind" welds were made with the operator watching only a stopwatch and the weld current ammeter. A weld was made between two tubes separated by a 1/32 inch gap to determine the effect of poor fit-up on the weld schedule and quality. After welding, the sleeve showed increased concavity but this concavity did not extend into the tube wall. The poor fit-up did not impair the weldability.

Welding Three Inch Diameter Tubing

A limited number of welds were made in three inch diameter, .065 inch wall, type 321 stainless steel tubing. These welds were made using about the same procedure as described for the one inch diameter tubing. The sleeves were made from expanded lengths of the same three inch diameter tubing. Both argon gas and "Aircomatic No. 75" shield gas were used on the torch side of the welds.

Tubing ovality caused some difficulty because of joint offset resulting from tube end mismatch. In some areas the joint offset was calculated to be from .020 to .040 inches. This amount of offset resulted in the weld penetration moving to one side causing lack of fusion across the joint. However, several other specimens which had as much as .030 inch mismatch were welded satisfactorily. These difficulties were overcome by selectively matching the tube ends. No special sizing techniques were used. Specific procedures for sizing and fit-up will be developed in Phase II during manufacture of the qualification test specimens.

Longer welding times were required for the large diameter tubing. Because of these long weld times the preheating effect from weld heat buildup becomes more noticeable and must be compensated for. Starting the weld at the 4 o'clock position caused a heavy drop-through when the weld reached the 12 o'clock position unless the welding current was reduced. This condiction was alleviated by welding halfway around the tube, stopping to permit the joint area to cool, and then completing the weld.

5.3 WELDING RENE' 41 TUBING

The Rene' 41 tubing which was welded during the Phase I part of the program was 3/4 inch diameter, .030 inch wall. The initial attempts to weld the Rene' 41 tubing were made with the one inch maximum diameter welding tool, but they were unsuccessful because of insufficient shielding gas coverage of the weld area. The shielding gas inlet in this tool does not rotate with the tungsten electrode. A rotating gas inlet could not be built into this unit because of the limiting size. The welding unit

which was designed and built under this program for welding three inch diameter tubing was sufficiently large so that a rotating gas inlet could be incorporated. This inlet moved with the electrode and so produced an improved inert gas shielding coverage of the weld area. However, when the 3/4 inch diameter tubing was welded with this tool, the gas inlet was located about one inch from the weld surface. A ceramic cup was bonded around the gas inlet and the electrode, as shown in Figures 25 and 26, to provide still further improvement in the direction of the shielding gas toward the weld surface. This change resulted in the gas inlet and electrode rotating around the tube as a unit, and the cup was able to direct the flow of the shielding gas directly on the weld surface. This cup is removed when this unit is used to weld larger diameter tubing. The modification solved the shielding gas coverage problem and permitted the joining of Rene' 41 tubing with satisfactory welds.

Good quality weld joints in 3/4 inch Rene' 41 tubing were made in both the vertical and horizontal positions. It was necessary, due to the preheating effect, to reduce the welding current after about two-thirds of the weld length around the tube had been completed. This condition was more apparent in the horizontal than in the vertical position, and is the result of the excess heat which increases the puddle fluidity and causes excessive drop-through. This condition also is aggravated by the gravitational effect during welding in the horizontal position.

A number of the welds were inspected metallographically and by radiography and were found to be satisfactory. One joint was found to have lack of penetration when inspected with a borescope. This joint was subsequently repaired by rewelding using a slightly "hotter" weld schedule with a current increase of 2 amperes. Re-inspection of the joint after this repair showed a good weld and indicated excellent penetration.

An oxidized surface was observed on the Rene' 41 welds. This oxide indicated that the cleaning by wire brushing and acetone wiping was not removing all of the scale from the tube. To insure removal of the scale and other contaminants which might have remained after the normal cleaning, the surfaces to be welded were also cleaned with sandpaper. This cleaning treatment resulted in welds with cleaner surfaces.

5.4 6061 ALUMINUM ALLOY TUBING

Many approaches were tried but no satisfactory method could be developed for "in place" fusion welding of aluminum tubing by use of the techniques to be investigated under this program. The high thermal conductivity, extreme fluidity of the weld puddle, and the oxide layer on the surface of the weld make it virtually impossible to join aluminum tubing using these techniques.

Small variations in fit-up, either between the sleeve fitting and the tube, or between the tube ends, cause serious heat shorts during welding. A gap in the butting ends of the tubes results in lack of fusion on one side of the joint.

A gap between the sleeve fitting and the tube can also result in lack of fusion in the tube. In some cases sufficient heat was transferred across the gap between the sleeve fitting and the tube to cause melting in both the sleeve and tube, but the two weld puddles remained separate and did not wet due to the oxide on the upper surface of the tube weld. In an attempt to cause the two puddles to wet, the surface of the tube was coated with Solar 202 weld flux. This resulted in better wetting but also caused excessive porosity in the weld.

A large gap between the tube and the sleeve fitting causes excessive melting in the sleeve and results in fouling of the tungsten electrode.

Finally, poor fit-up between the sleeve fitting and the tube causes a great variation in the preheating effect on the tube. This variation makes it extremely difficult to predict where the weld puddle will drop through the tube initially, and also to control the penetration once the puddle does drop through. Without control of puddle drop-through and penetration, automatic or "blind" welding of aluminum tubing joints cannot be accomplished.

In order to determine whether sufficient heat control was available for "in place" joining of aluminum tubing, several joints were welded in which the tube ends were butted together but the sleeve was eliminated. Puddle control was much better using this technique, but it was not possible to make any joints without producing about 50 percent concavity in the weld area. This concavity indicated a requirement for filler material.

Other methods of adding filler material are being considered in addition to the use of a sleeve. Joints were prepared in which rings having a "tee"-shaped cross-section were employed in place of a full cylindrical sleeve. The use of these "tee"-shaped cross-section rings caused additional problems in fit-up of the tube ends and also required tack welding for location purposes. During the subsequent welding of the tube joint, heat shorts occurred at each of the tack welds with a resulting lack of fusion. However, the use of the "tee"-shaped cross-section rings did show some promise. Some further work may be performed during Phase II to investigate an improved design for such rings. The anticipated effort would be small and would involve only the procurement or fabrication of the improved design ring and evaluation of its use in welded tube joints.

The use of filler wire appears to be the only method of filler material addition which has promise of resulting in an automatic production type process for weld joining aluminum tubing. This can be accomplished by the addition of a small wire feeder to the welding tool. This procedure was not evaluated during the Phase I work. However, a new tube welder is being designed for use with a separate program, Reference (27). This welder will be adaptable for use with a wire feeder, and is expected to be available within the next several months. This tool will then be used to determine the feasibility of weld joining aluminum tubing using automatic techniques with filler wire addition.

It should be noted that although the major problem encountered was that of obtaining a controllable heat input to the joint, other less important problems were also evident. The weld cross sections exhibited much porosity and occasional cracks, further emphasizing the requirement for filler wire addition. Normal practice for welding this 6061 aluminum alloy includes the addition of either 4043 or 5356 aluminum alloy filler wire.

5.5 ADDITIONAL WELDING DEVELOPMENT WORK REQUIRED

Final weld parameters will be developed for the actual tube diameters, wall thicknesses, and materials to be utilized for the Phase II qualification test specimens. Further investigation of filler wire addition for aluminum welding, as noted above, will be conducted. The Phase II work will include AM 350 stainless steel. AM 350 was not included in Phase I because sufficient development parameters had already been developed by prior NAA work.

6. PHASE II QUALIFICATION TEST PROGRAM

6.0 GENERAL

The objectives of the qualification tests are to determine and insure that the fittings are capable of operation under the performance and environmental conditions specified. The testing program will evaluate the brazed and welded fittings to demonstrate the qualification of the fittings to withstand the imposed design loads for the specified service lives, or to be as structurally sound as the tubing which the fittings join.

6.1 TEST FLUIDS

The following fluid media will be used during the tests specified in the following paragraphs:

(a) Gaseous helium

(b) Gaseous nitrogen

(c) Air

(d) Hydraulic Fluid, Petroleum Base, Military Specification MIL-H-5606

(e) Oronite 8200 Disiloxane Base Hydraulic Fluid, NAA Specification LB0145-100

(f) Aroclor 1248 Chlorinated Biphenyl Heat Transfer Fluid, manufactured by Monsanto Chemical Company

6.2 INSTRUMENTATION

The instrumentation to be used will consist of instrumentation commonly used for this type of testing. The data obtained will be verified, wherever possible, by obtaining readings with more than one type of instrument; e.g., both standard gages and also transducers may be used to measure fluid pressure.

6.3 SYSTEM SCHEMATIC

The basic system schematic for the hydraulic-pneumatic fluid system is shown in Figure 29.

6.4 DATA PRESENTATION

Test results will be presented in the form of tables, graphs, photographs of test set-ups and test components. Theoretical calculations and reproductions of the original data sheets will be included where applicable.

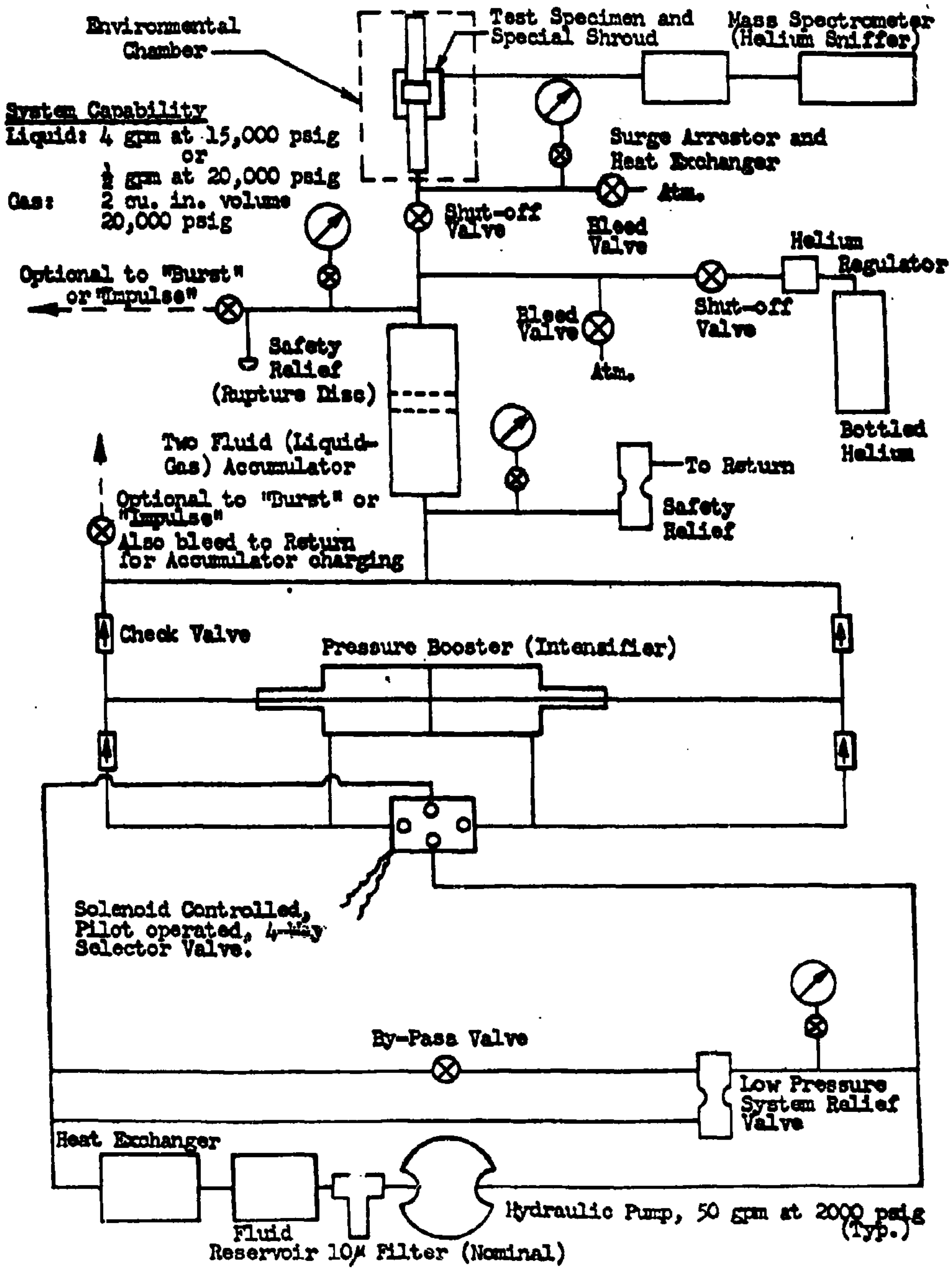


Figure 29. Qualification Test Installation — Basic Pressure System Schematic.

6.5 TEST PROCEDURES

General

The flow chart shown in Figure 30 presents the relationship between the several qualification tests and the sequence in which fittings will be subjected to the tests. Each individual type of test is described in the following paragraphs.

Initial Examination of Product

All test specimens will be inspected before test for conformance to the drawings and specifications which are applicable. Examination will be especially directed toward detecting possible defects in assembly or workmanship. Where required, test specimens will also be examined for defects after one or more of the qualification tests have been performed. This examination will assess the amount of damage, if any, incurred by the specimen during test. Results of this examination will be compared with the findings of the initial examination.

Proof Pressure and Leakage

Proof pressure for the joints to be tested is specified as 150 percent of maximum system operating pressure. The joint assembly is required to withstand this condition for five (5) minutes with no leakage or permanent distortion resulting. Leakage will be determined at the maximum design operating temperature, and also at -320 F. Gaseous helium will be used as the fluid medium, and a mass spectrometer will be used to detect any leakage. All test specimens will be subjected to this test prior to other qualification testing. Tests will be performed at the pressures and temperatures shown in Table XIII.

Burst Pressure

Burst pressure for the joints to be tested is specified as 200 percent of maximum system operating pressure. The joint assembly is required to withstand this pressure for a period of five (5) minutes at the maximum design operating temperature with no joint rupture resulting. Burst tests will be performed at the pressures and temperatures shown in Table XIII.

Repeated Assembly

This test is described herein, but may not be conducted if the joining processes are not found to be amenable to the repeated assembly procedure.

Repeated assembly specimens will be fabricated, inspected, subjected to the proof pressure and leakage test described above, and then reinspected. The specimens will then be disassembled, inspected, and if found satisfactory, reassembled by the same joining procedure as initially used. The definition of this test as set forth in the Contract for this program, Reference (1), requires the brazed specimens to be reassembled without addition of new brazing alloy.

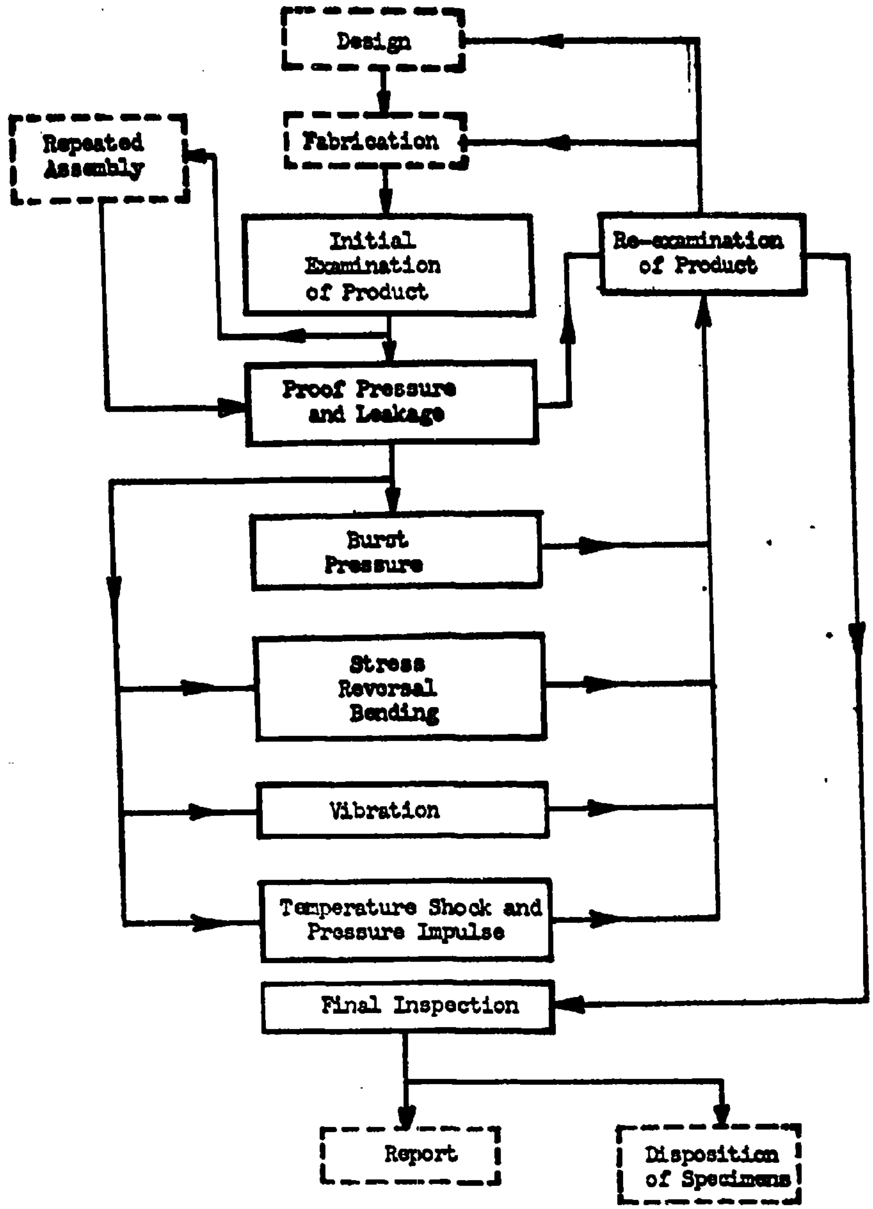


Figure 30. Flow Chart Showing Sequence of Qualification Tests.

TABLE XXXI. DESCRIPTION OF CONDITIONS FOR QUALIFICATION TESTS.

SERVICE	MATERIAL	SYSTEM OPERATING PRESSURE (psig)	TEST SPECIMEN TUBE SIZE (in.) O.D.	TEST SPECIMEN TUBE SIZE (in.) WALL THICKNESS	QUALIFICATION TEST DESCRIPTION	ONE EACH OF BRAZED AND WELDED SPECIMENS TO BE TESTED PER TEST TYPE WHERE MARKED -320F	Room	200F	600F	1500F
Propellant	Type 347 Stainless Steel	0 to 2500	1	.083	Burst			x		
					Stress Rev. Bend	x		x		
					Vibration			x		
					Temp. Shock	-		x		
					Pressure Impulse	x		x		
			3	.250	Burst			x		
					Stress Rev. Bend	x		x		
Pneumatic	6061-T6 Aluminum Alloy	0 to 3000	1/4	.049	Burst			w		
					Stress Rev. Bend	w		w		
					Vibration			w		
					Temp. Shock	-		w		
					Pressure Impulse	w		w		
		0 to 1000	1	.058	Burst			w		
					Stress Rev. Bend	w		w		
					Vibration			w		
					Temp. Shock	-		w		
					Pressure Impulse	w		w		
	AM 350 CRT Stainless Steel	0 to 10,000	1/4	.042	Burst				x	
					Stress Rev. Bend	x			x	
	AM 350 SCT Stainless Steel	0 to 10,000	1	.134	Burst				x	
					Stress Rev. Bend	x			x	
					Vibration				x	
					Temp. Shock	-			x	
					Pressure Impulse	x			x	
	Rene' 41	0 to 4000	1/8	.010	Burst					x
					Stress Rev. Bend	x	x			x
			1	.065	Burst					x
					Stress Rev. Bend	x	x			x
					Vibration					x
					Temp. Shock	-				x
					Pressure Impulse	x	x			x

Note: "x" indicates both welded and brazed fittings; "w" indicates welded fittings only to be tested.

Following each reassembly of the specimens, each specimen will again be put through the sequence of inspection, proof pressure and leakage test, and reinspection. The specimens will be required to go through the assembly, test, disassembly, and reassembly procedure five (5) times.

Stress Reversal Bending

These tests will consist of bending the test assemblies so as to impose a bending stress at the union centerline equivalent to 75 percent, maximum, of the yield strength of the joined tubing at the test temperature. A cantilever type configuration will be used and uniaxial bending will be imposed on the test specimen by means of an eccentric type drive which will produce a predetermined deflection at the cantilever end of the specimen. Calculated stresses will be corroborated by use of strain gages under static conditions at room temperature. The stresses under the dynamic and operating temperature conditions will be calculated.

Tests will be conducted at a bending cycle rate of approximately 1800 cpm for a maximum of 200,000 cycles, under the conditions shown in Table XIII. During these tests the specimens will be pressurized with gaseous nitrogen to 30 psig. A pressure drop of 10 psig will be used to indicate failure. Pressurized hydraulic fluid may then be used to determine the location of the failure.

Vibration

The vibration specimens will be of an indeterminate beam configuration (end fixity at both ends) rather than a cantilever configuration. A vibratory input amplitude will be utilized in the test sufficient to produce in the specimen at the union centerline a dynamic stress equivalent to 75 percent, maximum, of the yield strength of the joined tubing at the test temperature. A discrete frequency rather than frequency sweeping will be utilized for testing. Optical displacement indicating instrumentation will be used.

A theoretical calculation will be made for each material, each tube size, and each test temperature to determine the length of an indeterminate beam specimen which will resonate within the frequency limitations of existing optical instrumentation (150 to 180 cps).

Each specimen will be mounted in the test fixturing, heated to the testing temperature and stabilized at this temperature. Then, utilizing a low input vibratory forcing function, a frequency search from 10 to 2000 cps will be performed to determine acceptance and response modes, and transmissibilities at resonant conditions.

Each specimen will next be excited at the test temperature using sufficient input amplitude at the fundamental response frequency of the specimen to produce a stress at the union centerline equivalent to 75 percent, maximum, of the yield strength of the joined tubing at the test temperature for 2×10^6 cycles. If the response mode of the specimen changes with test duration, the frequency and/or input forcing function will be changed to maintain the stipulated stress.

Temperature Shock and Pressure Impulse

The temperature shock will be imposed by alternately impinging on the surface of the specimen assembly a flame (or a blast of heated air) and a stream of liquid nitrogen. The flame will be produced by propane burners. The stream of liquid nitrogen (-320 F) will be released from spray nozzles. A total of twenty-five (25) thermal shock cycles will be imposed in fifteen (15) minutes. During each temperature cycle the test assembly will also be subjected to internal pressure cycles of zero to 150 percent of maximum system operating pressure. Tests will be conducted according to the test conditions shown in Table XIII.

Pressure impulse tests will also be performed without the temperature shock. These tests will consist of pressure cycles ranging from zero to 150 percent of maximum system operating pressure, and will be conducted according to the test conditions shown in Table XIII.

The pressure impulse will be obtained by a pressure surge through a liquid medium utilizing a quick opening valve technique where applicable. The 1500 F and -320 F temperature pressure impulse testing will be conducted by cycling the test pressure from zero to 150 percent of maximum system operating pressure in a square wave pattern. A dwell at maximum pressure shall be incorporated. The rate for pressure impulse cycling will be 35 5 cpm.

Final Inspection

A final inspection will be performed on all test specimens and the results compared with those from previous inspections of the same specimen. After final inspection all test parts will be identified by a label and will be held for disposition according to the instructions of the USAF Project Officer.

6.6 TEST EQUIPMENT

General

The qualification test equipment will be constructed and installed in accordance with the NAA drawings listed below. Copies of the listed drawings have been furnished to the USAF Project Office.

X-4539	Heater and Specimen Holder for 1" Tube Flex Test
X-4540	Heater and Specimen Support for 1/8 and 1/4 Tube Flex Test
X-4544	Tube Flexing Fixture
X-4547	Tube Flexing Specimens
X-4548	Tube Specimens
X-4550	Furnace and Leak Trap for 1" Diameter Tube Specimen
X-4551	Furnace and Leak Trap for 3" Diameter Tube Specimen
X-4552	Furnace and Leak Trap for 1/8 and 1/4 Diameter Tube Specimen
X-4559	Thermal Shock Fixture for Tube Fittings
X-4561	Blast Shield for Tube Burst Test
X-4564	Holder and Load Arm for 3" Tube Specimen
X-4568	Vibration Fixture Development Brazed and Welded Fittings
X-4569	Test Specimens for X-4568 Vibration Fixture
X-4574	Temperature Shock Fixture -320° to 600°F

Pressurization Equipment

The following equipment and procedures will be used to produce the internal pressures in the test specimens.

The liquid intensifier will be used to pressurize the liquid fluid test media to the very high pressures. A Pressure Booster made by the Miller Fluid Power Division, Flick-Reedy Corporation, Bensenville, Illinois, has been designed and built to NAA specifications. This equipment will be used to boost 2000 psi hydraulic pressure to 20,000 psi pressure for the burst test requirement. The Booster can supply up to 4 gpm liquid flow (with a 50 gpm input) for the proof pressure and leakage test requirement.

The Pressure Booster will operate in the following manner. The 2000 psi pressure will be supplied by conventional pumps. The flow of liquid to the chamber or cavities of the Booster will be controlled by a directional control valve. The difference in area of the input piston and the output plunger produces a pressure boost of approximately 10 to 1. The system will be set up with check valves arranged to maintain almost continuous flow from the double-acting Booster. The Gas Intensifier Accumulator will serve to reduce the pressure fluctuations during Booster piston reversal.

A two-fluid Accumulator will be used in the Gas Intensifier system. The Accumulator was designed and built by Autoclave Engineers, Inc., to NAA specifications. This Accumulator will be used to store helium gas and to serve as a barrier between the high pressure liquid and the helium gas when the high pressure liquid discharged from the Pressure Booster is being used to pressurize the helium has. Prepressurized gas and/or a cascading technique can be used if the flow rate or volume requires. This system will be used for the proof pressure and leakage tests. Burst tests will be performed utilizing gas as the pressurizing medium only if the extreme temperatures encountered during certain tests precludes the use of liquids as the pressurizing medium.

Pressure impulsing will be accomplished in the following manner. Removal of the Accumulator from the liquid pressure system and slight cracking of the pressure by-pass valve will produce a square wave form of pressure impulse sufficient to meet the impulse test pressure requirements. The Booster will be cycled by means of a timer.

An alternate approach which may be used for the pressure impulse tests, should the square wave form of impulse prove undesirable, will use a quick-opening Aminco Valve, Model No. 44-5912, which will be driven by an electric motor through a gear box. This valve will serve to direct the high pressure fluid to the test specimen. A bleed or pneumatic-operated high pressure valve will reduce pressure to zero after closing of the quick-opening valve. The Accumulator will be installed upstream of the quick-opening valve to supply the short-time high flow rate required for a pressure surge.

Environmental Temperature Equipment

The following equipment will be used to attain the temperatures required for the test conditions shown in Table XIII.

Hevi-Duty Electric Co. exposed element radiation type heaters of the semi-cylindrical type will be used to produce 1500 F test temperatures. Thermocouples on the test specimen will be used to measure the test temperatures and for heater control.

An environmental chamber with air circulation convection heat, thermocouple controlled, will be used for the 200 F and 600 F tests.

The -320 F temperature for the stress reversal bending tests will be attained by flowing liquid nitrogen through the test specimen. A thermocouple on the test specimen will be used to verify the test temperature.

For the pressure impulse testing at -320 F, the test specimen will be immersed in a container of liquid nitrogen. Thermocouple control of the temperature of the pressurizing fluid will be used to insure that the fluid flow is sufficient to prevent the fluid from freezing. The test specimen temperature will also be checked by means of thermocouples.

For the -320 F to 1500 F thermal shock tests, the specimen will be alternately subjected to a flame from propane burners and to a stream of liquid nitrogen from appropriately arranged spray nozzles. The test specimen temperature will be determined by means of thermocouples.

The thermal shock tests at -320 F to 200 F, and also -320 F to 600 F, will utilize a hot air blast impinging on the test specimen alternating with a liquid nitrogen stream. Thermocouples will be used to determine test specimen temperatures.

REFERENCES

(1) USAF Contract No. AF 04(611)-8177, "Applied Research and Developmental Work on Families of Brazed and Welded Fittings for Rocket Fluid Systems," dated 1 April 1962.

(2) NAA Report No. NA-61-1069, "Technical Proposal for the Development of Lightweight Brazed and Welded Fittings for Service with Rocket Fluid Systems," dated 12 March 1962.

(3) Supplemental Agreement No. 2, dated 5 December 1962, to USAF Contract No. AF 04(611)-8177.

(4) Air Force Manual AFM 160-39, "The Handling and Storage of Liquid Propellants," dated March 1961.

(5) USAF Report No. AF/SSD-TR-61-7, "Hydrazine Handling Manual," dated September 1961.

(6) C. J. Thelan, "Materials Requirements for Storable Liquid Propellant Rocket Motors," Materials Science and Technology for Advanced Applications, ASM (1962), pp. 16-31.

(7) WADC Technical Report 56-414, "Corrosion and Ignition of Titanium Alloys in Fuming Nitric Acid," dated February 1957.

(8) USAF Report No. AS/SSD-TR-61-8, "Nitrogen Tetroxide Handling Manual," dated September 1961.

(9) C. W. Alley, A. W. Hayford and H. F. Scott, Jr.,"Effect of Nitrogen Tetroxide on Metals and Plastics," Corrosion, Vol. 17, October 1961, pp. 479t-484t.

(10) USAF Report No. AFFTC TR-60-62, "Storable Propellant Data for the Titan II Program, Quarterly Progress Report No. 1," dated October 1960.

(11) DMIC Memorandum 89, "Summary of Present Information on Impact Sensitivity of Titanium When Exposed to Various Oxidizers," Defense Metals Information Center, Battelle Memorial Institute, dated March 6, 1961.

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(13) NAA Rocketdyne Report No. R-3330P, "Air Force Tube Fitting Development Program," dated 29 November 1961.

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(18) NAA Material Properties Data Manual.

(19) Haynes Stellite Co. Data Booklet F-30,107-B, "Hastelloy Alloy C," dated September 1960.

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(22) B. A. Boley and J. H. Weiner, Theory of Thermal Stresses, John Wiley & Sons, Inc. (New York), 1960.

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(25) J. Marin and F. P. J. Rimrott, "Design of Thick-Walled Pressure Vessels Based Upon the Plastic Range," Welding Research Council Bulletin 41, July 1958.

(26) J. L. Lubkin and E. Reissner, "Stress Distribution and Design Data for Adhesive Lap Joints Between Circular Tubes," Transactions, ASME, August 1956.

(27) Portsmouth Naval Shipyard Contract No. N102-75318(X), "Design and Develop an Automatic Joint-Welding Device Suitable for Use In the Installation of Non-Nuclear Piping Systems in Nuclear Submarines," dated 20 August 1962.

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Unclassified Report

Recommendations are presented for (over)

I. Project 6753, Task 675304
II. Contract AF04(611)-8177
III. North American Aviation, Inc., Los Angeles, California.
IV. M. H. Weisman, et. al.

lightweight brazed and welded fittings for use with rocket propulsion fluid systems. Joining procedures and preliminary designs have been developed for induction brazed and TIG welded fittings for tubing of AISI 347 and AM 350 stainless steels and Rene' 41 alloy. Qualification test procedures and equipment have been prepared for use in Phase II.

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